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RESEARCH PROPOSAL AND ANNUAL REPORT
SUBMITTED TO THE OFFICE OF NAVAL RESEARCH

by

The University of Tennessee, Department of Physics
Knoxville, Tennessee 37916.

Title: Structure of Multiply Ionized Heavy Ions and Associated Collision Phenomena

Principal Investigator
Ivan Sellin
Professor of Physics
[redacted]
Department of Physics and Astronomy

Proposed Starting Date: 1 May 1978 Amount Requested: $57,000

Proposed Duration in Months: 12

Type of Proposal: Renewal of Contract N-00014-75-C-0474

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(This grant will be administered by The University of Tennessee. Dean Thomas has the authority to discuss and negotiate this contract.)

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ABSTRACT AND SUMMARY WORK STATEMENT

This proposal is for continuation of the operating support of on-going research on the atomic structure of highly ionized ions and associated collision phenomena. Experiments concerning multiply ionized ions in the range Z = 3 - 36 and as broad as possible an energy range are presently being carried out at the Oak Ridge National Laboratory, the Brookhaven National Laboratory, The University of Tennessee, the Gesellschaft für Schwerionenforschung, and occasional other sites, by a university users' group. This group presently consists of three University of Tennessee faculty members, two postdoctoral research associates, two graduate students, and a number of occasional collaborators from other institutions whose participation is frequent. The primary objective of our research remains the study of atomic structure of multiply ionized heavy ions and their modes of formation and destruction in collisions. Decay of excited states of these ions by radiative and also by electron emission processes is the phenomena observed in carrying out these experiments. Our principal tools are suitable sources and accelerators of multiply charged ions; x-ray, soft x-ray, and extreme ultraviolet spectrometers; electron spectrometers; lasers; on-line computer gear; and a variety of peripheral equipment associated with these devices.

Specifically it is proposed to: (1) study multiple electron excitation into projectile continuum states by impact of highly charged projectile ions on light atoms and molecules; (2) study the projectile charge state dependence of the production of Auger-emitting lithiumlike target ions by impact of highly charged projectile ions on lighter target atoms and molecules; (3) make delayed coincidence lifetime and quenching cross section measurements on long-lived Auger emitting states of such multiply ionized target atoms and molecules; (4) to begin the study of the energy and charge state distribution of the

recoil fragments in such encounters; (5) further study anomalies in the excitation function of core-excited levels of Li in Li^{+}-He collisions; (6) complete analysis of the lifetimes of electrostatic fine structure ($\Delta n = 0$) transitions in few-electron metal ions; (7) further examine the phenomenon of intensity beats in such $\Delta n = 0$ transitions within the M shell, particularly for $J = 1/2$ upper states; (8) make measurements of alignment tensor components in excited states of atoms produced by single collision encounters in gas targets.

DISCUSSION OF PRESENT AND PREVIOUS ONR-SUPPORTED RESEARCH

A. List of Publications on Research Accomplished under ONR Support, 1 November 1976 to date (present contract year, in inverse chronological order):

Books, Major Articles in Books, Reviews:

1. Structure and Collisions of Ions and Atoms, I. A. Sellin, ed. (Springer Verlag, Heidelberg), to be published in 1978.

2. Op. cit., Chapter 6, "Extensions of Beam Foil Spectroscopy."

3. "Radiative and Auger Beam Foil Studies," in Methods of Experimental Physics, Vol. 14, P. Richard, ed. (Academic Press, New York), to be published in 1978.

4. "Beam Foil Spectroscopy," in Scientific American, D. Flanagan, ed. (Scientific American, Inc., New York), to be published in 1978.

5. "The Violent Many-Electron Chemistry of Highly Charged Ions," in Physics News - 1977, G. Present, ed. (American Institute of Physics, New York), to be published in 1977.

Other Articles in Books, Major Journals, and Proceedings:

6. "The Violent Many-Electron Chemistry of Highly Charged Ions," to be published in Physics News - 1977, G. Present, ed. (American Institute of Physics, New York), 1977.

7. "Observation of Quantum Beats in Gas-excited Helium Projectiles," with J. Bromander and L. Liljeby, submitted to Zeitschrift für Physik, 1977.

8. "Studies of Neon L-Shell Excitation by Impact of Highly Ionized Heavy Ions," to be published in Zeitschrift für Physik, 1977.

9. "Radiative Lifetimes of the Low-lying Levels of Na-like Copper," to be published in Phys. Rev. A, November, 1977.

10. "Spin-dependent Excitation of Autoionizing States of Li Produced in Collisions with Noble Gas Targets," in Proceedings, Tenth International Conference on the Physics of Electronic and Aromic Collisions, M. Barat, J. Reinhardt, and G. Watel, eds. (Commissariat a l'Energie Atomique, Paris), p. 1014 (1977).

11. "Neon Characteristic X-ray Production in Neon-Neon Collisions as a Function of Incident Projectile Charge State," in Proceedings, Tenth International Conference on the Physics of Electronic and Atomic Collisions, M. Barat, J. Reinhardt, and G. Watel, eds. (Commissariat a l'Energie Atomique, Paris), p. 894 (1977).

12. "Recoil Ion Spectroscopy in the XUV-Soft X-ray Region Following Heavy Ion Impact on Thin Gas Targets," in Proceedings, Tenth International Conference on the Physics of Electronic and Atomic Collisions, M. Barat, J. Reinhardt, and G. Watel, eds. (Commissariat a l'Energie Atomique, Paris), p. 634 (1977).

13. "High Resolution Studies of Extensive Ne L-Shell Excitation by Energetic Heavy Ion Impact," in Proceedings, Tenth International Conference on the Physics of Electronic and Atomic Collisions, M. Barat, J. Reinhardt, and G. Watel, eds. (Commissariat a l'Energie Atomique, Paris), p. 632 (1977).

14. "Overcoming the Doppler Limitation in Beam-Foil Experiments by Target Ion Spectroscopy," in Proceedings, Fourth Conference on Scientific and Industrial Applications of Small Accelerators, J. L. Duggan and I. L. Morgan, eds. (International Association of Electrical and Electronic Engineers, Report 76 CH 1175-9 NPS, New York), p. 319 (1977).

15. "Intensity Modulations in the Decay of the $3^2P_{1/2}$ Level in the Sodiumlike Ion, Cu^{18+}," Phys. Rev. Lett. 38, 1471 (1977).

16. "Oscillator Strengths for In-Shell ($\Delta n = 0$) Dipole Transitions in Li- and Be-like Sulfur," Phys. Rev. A15, 1958 (1977).

17. "The Splitting and Oscillator Strengths for the $2s^2S$-$2p^2P^0$ Doublet in Lithiumlike Sulfur," Astrophysical J. 214, 331 (1977).

18. "Production of Soft X-Ray Emitting Slow Multiply Charged Ions: Recoil Ion Spectroscopy," Phys. Lett. 61A, 107 (1977).

19. "Projectile Charge-State Dependence in K-Shell Ionization of Neon, Silicon, and Argon Gases by Lithium Projectiles," Physics Lett. 60A, 292 (1977).

20. "Charge Dependence of K X-Ray Production in Nearly Symmetric Collisions of Highly Ionized S and Cl Ions in Gases," Phys. Rev. A14, 1997 (1976).

21. "Radiative Lifetimes and Transition Probabilities for Electric-dipole $\Delta n = 0$ Transitions in Highly Stripped Sulfur Ions," Phys. Rev. A14, 1036 (1976).

22. "Dipole Oscillator Strengths for $\Delta n = 0$ Transitions in Highly Ionized Sulfur," Physics Lett. 58A, 349 (1976).

Other Papers:

23. "Metastable Auger Emitter Lifetimes by a Delayed Coincidence Technique," to be published in Bull. Am. Phys. Soc., Nov. 1977.

24. "Quantum Beat Method of Measuring Alignments in Single Ion-Atom Collisions," to be published in Bull. Am. Phys. Soc., Nov. 1977.

25. "Stark Shifts and Broadening of Auger Lines of Highly Ionized Atoms in Molecules After Heavy Ion Impact," to be published in Bull. Am. Phys. Soc., Nov. 1977.

26. "Target Specificity Effects on the Production of Core-Excited States of Li and Li^+ for 10 to 50 keV Collisions of Li^+ with Gas Targets," to be published in Bull. Am. Phys. Soc., Nov. 1977.

27. "Decay Studies of n = 3 Transitions in Sodiumlike Bromine," to be published in Bull. Am. Phys. Soc., Nov. 1977.

28. "Lifetimes of the $2p\ ^2P_{1/2,3/2}$ States of Fe XXIV and the $2s2p\ ^3P_1^o$ State of Fe XXIII," to be published in Bull. Am. Phys. Soc., Nov. 1977.

29. "Lifetimes and Oscillator Strengths for $\Delta n = 0$ Dipole Transitions in C-, N-, O-, and F-like Chlorine," to be published in Bull. Am. Phys. Soc., Nov. 1977.

30. "Decay Measurements on the n = 2 States of Li-, Be-, and B-like Chlorine," to be published in Bull. Am. Phys. Soc., Nov. 1977.

31. "Radiative Lifetime Measurements on the n = 2 Levels of Al XI and P XII," to be published in Bull. Am. Phys. Soc., Nov. 1977.

32. "Oscillator Strengths for the Principal Resonance Transitions in Si XI and XII," to be published in Bull. Am. Phys. Soc., Nov. 1977.

33. "Measurement of Alignments in Single Ion-Atom Collisions by a Quantum Beat Method," presented at the Fourth International Seminar on Ion-Atom Collisions, Darmstadt, Germany, July 1977.

34. Invited paper, "Multiple Electron Rearrangement in Heavy Ion-Atom Collisions," presented at the Gordon Research Conference on Atomic Physics, Wolfsborough, New Hampshire, July 1977.

35. Invited paper, "Charge Exchange in Slow Collisions," presented at the Gordon Research Conference on Atomic Physics, Wolfsborough, New Hampshire, July 1977.

36. "Recoil Ion Spectroscopy: Reduction of Doppler Shifts and Spreads in Fast Beam Experiments," Bull. Am. Phys. Soc. 22, 610 (1977).

37. "Lower Limits on Resolved Neon L-shell Excitation Cross-sections by Impact of 1.5 MeV/A $\sim S^{12+}$, Cl^{12+} Ions," Bull. Am. Phys. Soc. 22, 609 (1977).

38. "Projectile Charge-State Dependence in K-shell Ionization of Neon, Silicon, and Argon Gases by Lithium Projectiles," Bull. Am. Phys. Soc. 22, 655 (1977).

39. "Production of Core-Excited States of Li and Li^+ in Collisions with Gas Targets," Bull. Am. Phys. Soc. 22, 655 (1977).

40. "Auger Electron Emission from Target Ions Under Heavy Ion Impact After Molecular Dissociation," Bull. Am. Phys. Soc. 22, 610 (1977).

41. "Lifetime Measurements in Cu XIX," Bull. Am. Phys. Soc. 22, 609 (1977).

42. "$\Delta n = 0$ Transitions in Highly Ionized Ions," in Proceedings, Nordic Symposium on Atomic and Molecular Transition Probabilities, I. Martinson, ed. (Lunds Univeristet, Lund), p. 8 (1977).

43. "Der $2s^2S-2p^2P^o$ Doublettübergang in Li-ähnlichem Schwefel," Verhandl., Deutsche Physikalische Gesellschaft 2/1977, 500 (1977).

44. "Lebensdauern und Oszillatørenstärken von n = 2 Zustanden in Be-ähnlichem S," Verhandl., Deutsche Physikalische Gesellschaft 2/1977, 500 (1977).

45. Invited paper, "Contributions of Beam-Foil Spectroscopy to Oscillator Strengths of Interest in High Temperature Plasmas," presented at the American Physical Society-Topical Conference on Atomic Processes in High Temperature Plasmas, Knoxville, February 1977.

46. "An Application of the Beam Foil Method to Transitions of Astrophysical Interest," presented at the American Physical Society Topical Conference on Atomic Processes in High Temperature Plasmas, Knoxville, February 1977.

47. "Decay Studies of n = 3 States of Sodiumlike Copper Using Foil Excitation," presented at the American Physical Society Topical Conference on Atomic Processes in High Temperature Plasmas, Knoxville, February 1977.

48. Invited paper, "High Ionization-Excitation States of Ne^{q+} Ions and their Mass-Dependent Symmetric Collision Interactions," presented at the Annual Meeting of the American Physical Society, Division of Electron and Atomic Physics, Lincoln, Nebraska, December 1976, Bull. Am. Phys. Soc. 21, 1250 (1976).

49. "Radiative Lifetimes and Oscillator Strength for the n = 2 States of Be-like Sulfur," Bull. Am. Phys. Soc. 21, 1253 (1976).

50. "A Beam-Foil Study of the $2s^2S-2p^2P^o$ Doublet in Li-like Sulfur," Bull. Am. Phys. Soc. 21, 1252 (1977).

51. "Mass Dependence of Ne K X-Ray Yields from Ne^+-Ne Collisions at keV Energies," Bull. Am. Phys. Soc. 21, 1248 (1976).

52. "Measurement of the H^++H Charge Exchange Cross Section, 0.8-2.5 MeV," in Bull. Am. Phys. Soc. 21, 1265 (1977).

53. Invited paper, "Overcoming the Doppler Limitation in Beam-Foil Experiments by Target Ion Spectroscopy," presented at the Fourth Conference on Application of Small Accelerators, Denton, Texas, October 1976, Bull. Am. Phys. Soc. 21, 1333 (1976).

B. List of Publications on Research Accomplished Under Previous ONR Support: Articles in Major Journals and Proceedings (in inverse chronological order):

Books, Major Articles in Books, Reviews:

1. Beam Foil Spectroscopy: Vol. 1, Atomic Structure and Lifetimes, Vol. 2, Collisional and Radiative Interactions, I. A. Sellin and D. J. Pegg, eds., Plenum Press, New York (1976).

2. "Highly Ionized Ions," in Advances in Atomic and Molecular Physics, Vol. 12, D. R. Bates and B. Bederson, eds., Academic Press, New York (1976), p. 215.

3. "Measurement of Auger Lifetimes and Energy Levels by Projectile Electron Spectroscopy," in Topics in Current Physics, Vol I: Beam-Foil Spectroscopy, S. Bashkin, ed., Springer-Verlag, Heidelberg(1976), Chap. 10, p. 265.

Other Articles in Books, Major Journals and Proceedings:

4. "Strong Isotope Dependence of K-Vacancy Production in Slow Ne^{+}-Ne Collisions," Phys. Rev. Lett. 37, 984 (1976).

5. "Differences in the Production of Non-Characteristic Radiation in Gaseous and Solid Targets," Phys. Rev. Lett. 36, 1574 (1976).

6. "An Experimental Survey of Electron Transfer in keV Collisions in Multiply Charged Ions with Atomic Hydrogen," in Proceedings of the Fifth International Conference on Atomic Physics, R. Marrus, M. H. Prior, and H. A. Shugart, eds., University of California, Berkeley, California (1976), p. 126.

7. "Lifetimes and Transition Rates for Allowed In-Shell Transitions in Highly Stripped Sulfur," in Proceedings of the Fifth International Conference on Atomic Physics, R. Marrus, M. H. Prior, and H. A. Shugart, eds., University of California, Berkeley, California (1976), p. 166.

8. "Polarization Measurements on the Non-Characteristic Radiation Emitted from Collisions Between High Energy Aluminum Ions," Phys. Letters A56, 89 (1976).

9. "Applications of Beam-Foil Spectroscopy to Atomic Collisions in Solids," Nucl. Inst. and Meth. 132, 397 (1976).

10. "Differences in the Production of Non-Characteristic Radiation in Solid and Gas Targets," in Beam-Foil Spectroscopy: Heavy Ion Atomic Physics, I. A. Sellin and D. J. Pegg, eds., Plenum Press, New York (1976), Vol. 2, p. 497.

11. "Angular Distribution Studies on Non-Characteristic X-Radiation," in Beam-Foil Spectroscopy: Heavy Ion Atomic Physics, I. A. Sellin and D. J. Pegg, eds., Plenum Press, New York (1976), Vol. 2, p. 497.

12. "Autoionizing States in Highly Ionized O, F, and Si," in Beam-Foil Spectroscopy: Heavy Ion Atomic Physics, I. A. Sellin and D. J. Pegg, eds., Plenum Press, New York (1976), Vol. 1, p. 451.

13. "Autoionizing States in the Alkalis," in Beam-Foil Spectroscopy: Heavy Ion Atomic Physics, I. A. Sellin and D. J. Pegg, eds., Plenum Press, New York (1976), Vol. 1, p. 419.

14. "Extreme Ultraviolet Spectra of Highly Stripped Si Ions," in Beam-Foil Spectroscopy: Heavy Ion Atomic Physics, I. A. Sellin and D. J. Pegg, eds., Plenum Press, New York (1976), Vol. 1, p. 321.

15. "Core-Excited Autoionizing States in the Alkalis," Phys. Rev. A12, 1330 (1975).

16. "Autoionizing States Formed in Na^{+} + Ne and Mg^{+} + He Collisions at 70 keV," in Electronic and Atomic Collisions, J. S. Risley and R. Geballe, eds., University of Washington Press, Seattle, p. 869 (1975).

17. "Photon Energy Dependence of the Asymmetry of Non-Characteristic X-Radiation in Si-Al and Al-Al Collisions," in Electronic and Atomic Collisions, J. S. Risley and R. Geballe, eds., University of Washington Press, Seattle, p. 312 (1975).

18. "Heliumlike ^{19}F; 2^3P_2 and 2^3P_0 Lifetimes," Phys. Rev. A11, 2198 (1975).

19. "Symmetric Ion-Atom Collisions at Medium Energies:Non-Characteristic Radiation," Phys. Rev. A11, 468 (1975).

20. "Charge State Dependence of Si K X-Ray Production in Solid and Gaseous Targets by 40 MeV Oxygen Ion Impact," in Atomic Collisions in Solids, S. Datz, ed., Plenum Press, New York (1975), p. 461.

21. "Lifetimes of the Metastable Autoionizing $(1s2s2p)^4P_{5/2}$ States of Lithiumlike Al^{10+} and Si^{11+} Ions; Comparisons with theory over the Isoelectronic sequence Z = 8-18," Phys. Rev. A11, 468 (1975).

22. "Variation of the Anisotropy of the Non-Characteristic X-Rays Emitted from Fast Ion-Atom Collisions," in Proceedings of the Third Conference on Applications of Small Accelerators, ERDA CONF-74 1040 P1, p. 78 (1975).

23. "Symmetric Ion-Atom Collisions at Medium Energies: Characteristic X-Rays," Phys. Rev. A11, 135 (1975).

24. "Projectile Electron Emission Spectroscopy on Optically Inaccessible Autoionizing States in the Alkali Metals," Physics Lett. 50A, 447 (1975).

25. "Observation of Large and Strongly Energy Dependent Directional Anisotropies in Non-Characteristic K X-Rays Emitted in Heavy Ion Collisions," Phys. Rev. Lett. 34, 64 (1975).

26. "Characterization of Charge States of Energetic Ions in Solids from Associated K X-Ray Production, Phys. Rev. Lett. 33, 733 (1974).

27. "Autoionization Lifetimes of the Metastable $(1s2s2p)^4P_{5/2}$ State in the Lithiumlike Ions Al^{10+}, Si^{11+}, and S^{13+}," published in Proceedings, The Fourth International Conference on Atomic Physics, Heidelberg, Heidelberg Univ. Press, Heidelberg, W. Germany (1974), p. 79.

28. "XUV Spectra of Highly Ionized Fluorine and Oxygen," Phys. Rev. A 10, 745 (1974).

29. "New Lines in the XUV Spectrum of Heliumlike Fluorine, " Physics Letters 47A, 469 (1974).

30. "Radiative Transitions in Two-Electron Oxygen," Physics Letters 47A, 433 (1974).

31. "Neon K_α, K_β Satellite Structure Induced by 80-MeV Argon Ion Impact," Phys. Rev. A10, 1446 (1974).

32. "Lifetime and Binding Energy of the Metastable $(1s2s2p)^4P^0_{5/2}$ States in S^{13+}," Phys. Rev. A9, 1112 (1974).

33. "Observation of K X-Rays from Highly Ionized States of Neon Produced by 40 MeV Cl^{+7}, Cl^{+11}, and Cl^{+13} Beams," Phys. Rev. A9, 1470 (1974).

34. "Initial UNISOR Research: New Isotopes ^{186}Tl, ^{188}Tl, ^{116}I; Decays of $^{189,190}Tl$, ^{111}Xe, and ^{111}I; and Off-Line Atomic and Nuclear Studies," published in the Proc. of the 24th Ann. National Conf. of the Academy of Sci. USSR on Nuclear Spectroscopy and Structure of the Atomic Nucleus (1974).

35. "Projectile Charge State Dependence of K X-Ray Production by 1-4 MeV/amu Heavy Ions in Gases," Phys. Rev. A9, 644 (1974).

36. "Observation of Coherent Electron Density Distribution Oscillations in Collision-Averaged Foil Excitation of the n=2 Hydrogen Levels," Phys. Rev. Lett. 31, 1335 (1973).

37. "Electron Decay in-Flight Spectra for Autoionizing States of Highly Stripped Oxygen, Fluorine, Chlorine, and Argon Ions," Phys. Rev. A8, 1350 (1973).

38. "One- and Two-Electron Excited States Produced by Electron Exchange, Excitation, and Electron Capture in Collisions of Fluorine Ions in Argon Gas at 34.8 MeV," Phys. Rev. Lett. 31, 684 (1973).

39. "Exponential Projectile Charge Dependence of Ar K and Ne X-Ray Production by Fast, Highly-Ionized Argon Beams in Thin Neon Targets," Phys. Rev. Lett. 30, 1289 (1973).

40. "Metastable Autoionizing States," Nucl. Instr. and Meth. 110, 477 (1973).

41. "Electron Spectroscopy of Foil-Excited Chlorine Beams," Nucl. Instr. and Meth. 110, 489 (1973).

42. "Mean Life of the Metastable 2^3P_1 State of the Two-Electron Fluorine Ion," Phys. Rev. A8, 145 (1973).

43. "Exponential Projectile Charge Dependence of Ar K and Ne K X-Ray Production by Fast, Highly Ionized Argon Beams in Thin Neon Targets," Proceedings, Eighth International Conference on the Physics of Electronic and B. Cobic and M. Kurepa, editors, Graficko Preduzece Buducnost, Zrenjanin, Yugoslavia (July, 1973), p. 727.

44. "Metastable States of Highly Excited Heavy Ions," in Atomic Physics 3, Plenum Press, London, p. 327 (1973).

45. "Equilibrium Fractions for the Lowest Metastable Quartet States of Lithiumlike Oxygen and Fluorine Ions Traversing Carbon Foils," Phys. Rev. A7, 487 (1973).

46. "Metastable Autoionizing States in Sodium-like Chlorine," Phys. Rev. Lett. 28, 1615 (1972).

47. "Metastable Autoionizing States of Highly Excited Heavy Ions," Phys. Rev. Lett. 28, 1229 (1972).

Other Papers:

48. "Beam Foil Radiative Lifetime Measurement in Si IX - Si XIII," Bull. Am. Phys. Soc. 21, 689 (1976).

49. "Characteristic K X-Ray Production from High Energy Al-Al Collisions," Bull. Am. Phys. Soc. 21, 650 (1976).

50. "Radiative Electron Capture Cross Sections for High Energy Al-Al and Al-C Collisions," Bull. Am. Phys. Soc. 21, 650 (1976).

51. "Lifetimes and Spectra of Highly Ionized Sulfur," Bull. Am. Phys. Soc. 21, 626 (1976).

52. "Single and Double Electron Transfer in B^{q+} (q=2,3,4) Collisions with He, Ar, and H_2," Bull. Am. Phys. Soc. 21, 549 (1976).

53. Invited Paper, "Beam-Foil Studies of Highly Ionized Atoms," Bull. Am. Phys. Soc. 21, 508 (1976).

54. Invited Paper, "Highly Ionized Ions," Bull. Am. Phys. Soc. 21, 186 (1976).

55. "Comparison of Production of Non-Characteristic X-Ray Radiation in Solid (Al) and Gaseous (SiH_4) Targets," Bull. Am. Phys. Soc. 20, 1450 (1975).

56. "Beam-Foil Spectra of Iron, Copper, and Silicon," Bull. Am. Phys. Soc. 20, 1452 (1975).

57. Invited Paper, "Projectile Electron Spectroscopy of Autoionizing States in the Alkalis," Bull Am. Phys. Soc. 20, 826 (1975).

58. "Autoionizing States in Lithiumlike Si and Sodiumlike Cl," Bull. Am. Phys. Soc. 20, 679 (1975).

59. "Electron Spectra from Autoionizing States of Highly Stripped Oxygen and Fluorine," Bull. Am. Phys. Soc. 20, 679 (1975).

60. "Non-Characteristic Spectra from Symmetric and Asymmetric Collision Systems," Bull. Am. Phys. Soc. 20, 675 (1975).

61. "Electron Spectra from the Autoionizing Decay of Collisionally Excited Mg^+ and K^+ Beams," Bull. Am. Phys. Soc. 20, 674 (1975).

62. "Charge State Dependence of X-Ray Production of Collisions of Ni ($\sim$ 1 MeV/amn) with SiH_4," Bull. Am. Phys. Soc. 20, 639 (1975).

63. Invited Paper, "Directional Anisotropies in Non-Characteristic X-Ray Emission," Bull. Am. Phys. Soc. 20, 607 (1975).

64. "Energy Dependence of the Directional Anisotropy Exhibited by Quasimolecular K X-Radiation," Bull. Am. Phys. Soc. 20, 75 (1975).

65. "Electron Spectroscopy of Autoionizing States in LiI and NaI," Bull. Am. Phys. Soc. 19, 1184 (1974).

66. "Lifetimes and Binding Energies of the Metastable Autoionizing $(1s2s2p)^4P_{5/2}$ State in Al^{10+} and Si^{11+}," Bull. Am. Phys. Soc. 19, 1176 (1974).

67. "Characterization of Charge States of Energetic Ions in Solids from Associated K X-Ray Production," Bull. Am. Phys. Soc. 19, 1184 (1974).

68. Invited Paper, "Recent Coherent Excitation and XUV-X-Ray Spectroscopy Experiments of Some Interest to Nuclear and Optical Physicists," Bull. Am. Phys. Soc. 19, 586 (1974).

69. "Observations of Non-Characteristic Combined Atom K-shell X-Ray Band in Al-Al Collisions," Bull. Am. Phys. Soc. 19, 590 (1974).

70. "X-Ray Cross Sections in Symmetric Ion-Atom Collisions," Bull. Am. Phys. Soc. 19, 570 (1974).

71. "Charge State Dependent Energy Shifts of K X-Rays Accompanying Nearly Symmetric Collisions of $\sim$ 3 MeV/amu S and Cl Ions," Bull. Am. Phys. Soc. 19, 590 (1974).

72. "n=2 Finestructure Decays in He-Like F," Bull. Am. Phys. Soc. 19, 468 (1974).

73. "K X-Ray Yields from Single Collisions of ∿ 100 MeV Cl Ions with Si," Bull. Am. Phys. Soc. 19, 590 (1974).

74. "Ne and Ar K X-Ray Satellite Production," Bull. Am. Phys. Soc. 19, 570 (1974).

75. "Improvements in the Use of Grazing Incidence Spectrometers to Study Spectra of Low Intensity, Highly Stripped Ion Beams," Bull. Am. Phys. Soc. 19, 469 (1974).

76. "XUV Spectra of Highly Stripped Oxygen and Fluorine," Bull. Am. Phys. Soc. 19, 469 (1974).

77. "Observation of K X-Rays from Highly Ionized States of Neon Produced by 40 MeV Cl^{+7}, Cl^{+11}, and Cl^{+13} Beams," Bull. Am. Phys. Soc. 19, 89 (1974).

78. "Observation of Coherently Excited Dipole Charge Distribution Oscillations in Collision - Averaged Foil Excitation of the n=2 H Levels," Bull. Am. Phys. Soc. 18, 1527 (1973).

79. "Effective Charge State of Heavy Ions Penetrating Solids Deduced from Comparing X-Ray Yields in Gases and Solids," Bull. Am. Phys. Soc. 18, 1508 (1973); presented at the Third International Conference on Atomic Collisions in Solids, Gatlinburg, Tenn., Sept., 1973 .

80. "Projectile Structure Effects in Heavy-Ion-Induced K X-Rays: Projectile X-Rays," Bull. Am. Phys. Soc. 18, 1508 (1973).

81. "Projectile Structure Effects in Heavy-Ion-Induced K X-Rays: Target X-Rays," Bull. Am. Phys. Soc. 18, 1508 (1973).

82. "Binding Energy and Lifetime of the $(1s2s2p)^4P^0_{5/2}$ State in Lithiumlike Sulfur," Bull. Am. Phys. Soc. 18, 1527 (1973).

83. "Electron Spectra from the Decay-in-Flight of Metastable Autoionizing States Associated with Highly Excited Heavy Ions," Bull. Am. Phys. Soc. 18, 1527 (1973).

84. "Mean Life of the Metastable 2^3P_1 State of the Two-Electron Fluorine Ion," Bull. Am. Phys. Soc. 18, 610 (1973).

85. Invited Paper: "Autoionization of Atoms Produced in Heavy Ion Collision," in Proceedings of the ORNL Heavy-Ion Summer Study Oak Ridge, Tennessee, AEC CONF-720669, 551 (1972).

C. Synopsis of Principal ONR-Supported Research Accomplishments of the Present Contract Year

C.1. Production of Multiple Electron Excitation and Ionization By Impact of Highly Charged Projectile Ions on Light Atoms and Molecules

One of the first results of our then newly funded accelerator-based atomic physics program was discovery of very large projectile charge state effects on multiple electron vacancy production in both inner and outer shells of light atoms and molecules (Phys. Rev. Lett. 29, 1577 (1972) and Phys. Rev. Lett. 30, 1289 (1973)). In these and subsequent papers (e.g., Phys. Rev. A9, 644 (1974) and Phys. Rev. A10, 1446 (1974)) we were able to show that in a typical case like Ar^{18+} incident on Ne gas atoms at impact parameter intermediate between Ne K and L shell radii, violent events like simultaneous removal of 9 of the 10 neon electrons accompanied by excitation of the 10th (e.g., to the hydrogenic ion 2p state) had substantial cross sections, even under single collision conditions. Indeed, total cross sections for removal of a K-shell electron turned out to have values larger than geometrical, and to be accompanied by removal of at least half of the L-shell electrons in most such collision events.

It has never been clear what ultimately happens to the ejected electrons, either experimentally or theoretically. Do they end up in excited but bound states of the target particle or of the projectile? Or do they end up in continuum states, and if so, centered on which particle? Or if all of these events occur, what are the likelihoods of the various outcomes?

Some experiments to investigate some of these questions were undertaken in the previous contract year, and continued to completion in the present contract year. Still others are proposed for the subsequent contract year in Section D.1 of this proposal. We now discuss work completed in the present contract year.

C.1.1. Multiple L Shell Excitation of Ne Gas by $S^{\sim 12+}$, $Cl^{\sim 12+}$ Projectiles; Target Ion Recoil Spectroscopy Experiments at ORNL.

In these experiments, passage of foil-excited 1.4 MeV/A S and 1.1 MeV/A Cl ions of mean charge state $\sim 12^+$ through neon gas targets at pressure $\sim$ 100 mTorr has been found to be accompanied by copious production of Ne II-VIII excited states. Comparable excitation cross-sections $\sim 10^{-18}$ cm^2 are found for a large number of levels belonging to all of these charge states and corresponding to principal quantum numbers n = 2,3,4. Because the Ne recoil velocities are small compared to the fast beam velocities characteristic of the beam-foil source, it is possible to reduce both Doppler shifts and spreads by 3-4 order of magnitude for equivalent collimation.

Estimates of recoil broadening are attractively low for two reasons. First, the long range, intense field of a highly ionized projectile permits electron removal and excitation processes for impact parameters larger than the shell radii of the affected target electrons. Second, the high relative collision velocity ($\gtrsim$ 0.05 c) provides a short interaction time, giving rise to slow recoil ions recoiling at almost exactly 90 deg to the beam direction. For example, a bare 2 MeV/A Ar nucleus passing by a Ne atom at an impact parameter of $\sim$ 1/3 Å--a Ne L-shell radius--creates a Ne recoil ion travelling at about 89.99 deg to the beam direction at a recoil velocity $v_R \lesssim 2\ v_B(M_{RED}/M_{Ne}) \cos \phi_R \cong 3 \times 10^5$ cm/sec $\cong 10^{-5}$ c. Here v_B is the beam velocity, M_{RED} the reduced mass, and ϕ_R the laboratory recoil angle. Hence $v_R/c \ll v_B/c$ by almost four orders of magnitude. For viewing angles and collimation equivalent to those prevailing in beam-foil experiments, both Doppler shifts and spreads in recoil vs. projectile lines--including Auger lines--should be smaller by about the same factor. Moreover, v_R is only of the order of thermal velocities in a hollow cathode discharge, a standard source for xuv/soft x-ray lines from single-particle valence shell excited states of ions in low states of ionization.

In this work we have shown by direct measurement that L-shell excitation cross-sections are attractively large for a wide range of ionization-excitation states, and that within the limitation of our present spectroscopic apparatus the low recoil estimates are fully justified. We have also found that the Ne target L-excitation spectrum is highly similar to that of a $\sim$ 1 MeV foil-excited Ne beam (Buchet and Druetta, JOSA 65, 91 (1975)), even though typical ion recoil velocities are a few thousand times smaller; that the L-shell excitation cross sections are of comparable magnitude ($\sim 10^{-18}$ cm^2) and only weakly dependent on charge state in the range of measurement (II-VIII); that there is a projectile charge state effect on the L-excitation cross-sections of a factor $\sim$ 5 for a corresponding projectile charge state change from 6^+ to $\sim 12^+$; that classification of K x-ray satellite spectra by L shell vacancy labels ($KL^0, KL^1, \cdots$) is probably misleading and oversimplified because of extensive population of $n \gtrsim 3$ spectator levels; that both the recoil ion and beam-foil spectra exhibit few lines corresponding to $n \gtrsim 4$ for incompletely understood reasons; and that with the possible exception of metastable levels, excited state quenching effects due to collisions with other gas atoms in the target are negligible.

An approximate excitation cross-section based upon the intensity of the Ne II standard line at λ 460.7 and our experimental conditions is $\gtrsim 3 \times 10^{-18}$ cm^2. While the estimate allows for grating reflectivity, astigmatism, and multiplier efficiency in addition to the more straightforward geometry factors, it does not allow for additional loss due to dispersion into higher diffraction orders nor for notoriously difficult estimates of loss due to possible time-dependent grating surface condition reflectivity losses. Hence this cross-section estimate should be regarded as an approximate lower limit. Corresponding lower limits on excitation cross-sections for other lines can be inferred from their relative intensities, provided account is taken of the grating blaze angle and wavelength dependent astigmatism.

The accompanying table provides a list of intense lines observed; their assigned configurations and terms where known from other reference sources; their intensities relative to λ 460.7 after adjustment for astigmatism, blaze, and electron multiplier efficiency; and the consequent approximate lower limits for excitation cross-sections from 1.4 MeV/amu $S^{\sim 12+}$ ion impact. Asterisks denote a very few transitions which appear in the present spectrum which were not noted in the beam foil spectrum of Buchet and Druetta.

The attractively large sizes of the lower limits on excitation cross sections which are furthermore seen to be approximately independent of target charge state indicates a bright future for experiments dependent on such target ion spectra, particularly if the widths of target lines are sufficiently low. Because target x-ray spectra from similar experiments involving impact of highly ionized projectiles have been characterized by line widths in the range 0.3 to 3 eV, we sought to improve on experimental limit on the line

TABLE I. Intense Ne lines observed, associated transitions, relative intensities, and approximate lower limits on cross-sections, adjusted for astigmatism, blaze, and electron multiplier efficiency for 1.4 MeV/nucleon S^{-12+} projectiles. Asterisks refer to transitions not noted in the beam spectrum of Buchet and Druetta.

(Å)	Spectrum	Transition		Relative Intensity	Cross-section (Mb) Limit
82.2*	VII	$2s2p\ ^1P^o$	$-2s4d\ ^3D$	60	0.2
88.1*	VIII	$2s\ ^2S$	$-3p\ ^2P^o$	90	0.3
98.2	VIII	$2p\ ^2P^o$	$-3d\ ^2D$	80	0.3
100.3	?	?	?	140	0.4
102.5*	?	?	?	190	0.6
106.2	VII	$2s2p\ ^3P^o$	$-2s3d\ ^3D$	170	0.5
111.2	VII,VI	$2p^2,2s^22p$	$-2p3d,2s2p(^3P^o)3p$	100	0.3
120.5	VII	$2p^2\ ^3P$	$-2p3s\ ^3P^o$	90	0.3
122.5	VI,V	$2p,2p^2$	$-3d,2p4d$	120	0.4
136.2	VI,V	$2s2p^2,2s2p^3$	$-2s2p3s,2s2p^2(^4P)4s$	120	0.4
138.5	VI	$2s2p^2\ ^2S$	$-2s2p(^3P^o)3d\ ^2P^o$	90	0.3
142.5	V*	$2p^2\ ^3P$	$-2p3d\ ^3P^o$	170	0.5
147.1	V*	$2p^2\ ^1D$	$-2p3d\ ^1F^o$	320	1.0
154.5	V	$2p^2\ ^1S^o$	$-2p3d\ ^3D$	270	0.8
184.7	V	$2p^2\ ^1S$	$-2p3s\ ^1P^o$	100	0.3
212.6	IV	$2p^3\ ^2D^o$	$-2p^2(^1D)3s\ ^2D$	280	0.8
222.6	IV	$2p^3\ ^2P^o$	$-2p^2(^1D)3s\ ^2D$	360	1.1
~234.3	IV	$2p^3\ ^2P^o$	$-2p^3(^3P)3s\ ^2P$	250	0.8
~283.7	III	$2p^4\ ^3P$	$-2p^3(^2D^o)3s\ ^3D^o$	240	0.7
301.1	III	$2p^4\ ^1D$	$-2p^3(^2D^o)3s\ ^1D^o$	230	0.7
379.3	III	$2s^22p^4\ ^1D$	$-2s2p^5\ ^1P^o$	750	2.3
405.9	II	$2p^5\ ^2P^o$	$-2p^4(^1D)3s\ ^2D$	400	1.2
407.1	II	$2p^5\ ^2P^o$	$-2p^4(^1D)3s\ ^2D$	200	0.6
416.8	V	$2s^22p^2\ ^1S$	$-2s2p^3\ ^1P^o$	170	0.5
455.3	II	$2p^5\ ^2P^o$	$-2p^4(^3P)3s\ ^4P$	400	1.2
460.7	II	$2s^22p^5\ ^2P^o$	$-2s2p^6\ ^2S$	1000	3.0
462.4	II	$2s^22p^5\ ^2P^o$	$-2s2p^6\ ^2S$	500	1.5

widths of a typical transition (the Ne II standard line λ 460.7) to $\lesssim$ 7 meV, a factor of 50 to 500 improvement (about an order of magnitude on a $\lambda/\Delta\lambda$ basis). As the monochromator was operated at its limit of resolution for this measurement, the measured width was verified to be entirely instrumental. As noted above, the actual line width is suspected to be an order of magnitude smaller, because of the small estimated values of recoil velocity ($\sim 10^{-5}$ c). Additionally, a projectile charge state effect of a factor $\sim$ 5 was noted in the intensity of many target lines in going from use of the primary accelerator beams (6^+) to foil-stripped beams ($\sim 12^+$).

Beyond establishing the magnitude of associated production cross-sections and limits on Doppler broadening, there is thus evidence of extensive population of intially unpopulated n = 3, 4 levels which if also present in K-ionizing collisions constitute extensive population of spectator electron levels not previously noted. Both the recoil-ion and beam-foil spectra exhibit few lines corresponding to upper states with n $\gtrsim$ 4. Collisional quenching effects on excited levels having lifetimes typical of the high ionization-excitation states considered here are not only expected to be negligible at the target densities used but are found to be so for the typical transition at λ 147.1 for which this assertion was checked.

How to understand the relative rarity of n = 4 upper levels and the nearly complete absence of intense transitions from n $\gtrsim$ 5 presents problems. A plausible partial explanation is that n $\gtrsim$ 4 excitations are often accompanied by a second n $\gtrsim$ 3 excitation, resulting in intense deexcitation competition through the Auger effect, suppressing effective line intensities by a factor of $\sim 10^2$ to 10^5. The comparable production of ionization states II-VIII tends to support this suggestion, in that Auger cascades leading to increased production of the higher charge states could be initiated by intense multiple L-shell excitation followed by increasing ionization through successive Auger processes.

Another effect which could in principle account for the relative rarity of lines corresponding to $n \geq 4$ is the quenching of such states in collisions in the gas target in less than a radiative lifetime. Such quenching is however unexpected, since in typical state lifetimes $\sim$ 10-100 psec at velocities of $\sim 10^{-5}$ c, a mean free path of only $\lesssim$ 1000 Å occurs. Hence for quenching cross-sections even as large as 10^{-14} cm^2, negligible quenching should occur. Only for metastable states of mean life $\gtrsim$ 10 nsec would such quenching cross-sections in gas targets at $\gtrsim$ 300 mTorr pressure be likely to cause appreciable quenching. Indeed, a plot of the λ 147.1 intensity to pressure ratio vs. pressure had only a slight (-8% ± 10%) slope consistent with zero quenching. The upper state in this transition is 2p3d $^1F^o$, a typical configuration among those found to be strongly populated.

Some additional valuable properties of the kind of target ion spectroscopy described here may be noted. First, the excited ions of interest are produced in an environment which is cold compared to both traditional hollow cathode discharges and to plasma sources. Collisional broadening and corresponding lifetime perturbation effects will be much reduced. Second, current technology permits recovery of one of the most valuable features of the beam-foil source, namely the ability to make lifetime measurements. Pulsed beams in the nanosecond regime are standard at numerous accelerator facilities. Delayed coincidence measurements of the time interval between the beam pulse and photon emission are a well-known, standard technique which should permit lifetime measurements on excited states of target ions in the nanosecond to tens of microseconds range.

This technique has in fact been tested on long-lived Auger emitting states of lithiumlike ions in collaborative experiments with a University of Frankfurt/M. group at the GSI accelerator in Germany. We now proceed to describe these experiments.

C.1.2. Multiple Electron Core Excitation of Target Atoms and Molecules by Highly Ionized Projectiles: Delayed Coincidence Auger Lifetimes and Quenching Experiments, Post-Collision Auger Lifetime Effects, and Charge State Dependence Experiments at GSI

During the period 1 April - 1 September 1977 the author collaborated extensively in experiments at the GSI accelerator at Darmstadt, West Germany. This accelerator is described in the Section on Facilities. The history of this collaboration was described in our proposal of one year ago, and is updated in the final sub-section of Section C and in the discussion of UNILAC in the Facilities section. We concentrate here on a technical description of results obtained.

As noted at the end of C.1.1., lifetime measurements on slow, multiply ionized and excited recoil ions should be feasible using a delayed coincidence technique. Our demonstration experiments at GSI have been very successful. Figure 1 shows a schematic diagram of the apparatus used for these delayed coincidence measurements. Using this apparatus, we have measured the lifetime of the 1s2s2p $^4P_{5/2}$ state in O^{5+}, produced by ions like Ar^{12+}, Kr^{26+} from the UNILAC accelerator in an O_2 target. Comparison with earlier beam foil results shows good agreement, better intrinsic precision, and establishes that cascade phenomena cause negligible errors in either technique. Data on $^4P_{5/2}$ quenching in O_2 was also obtained.

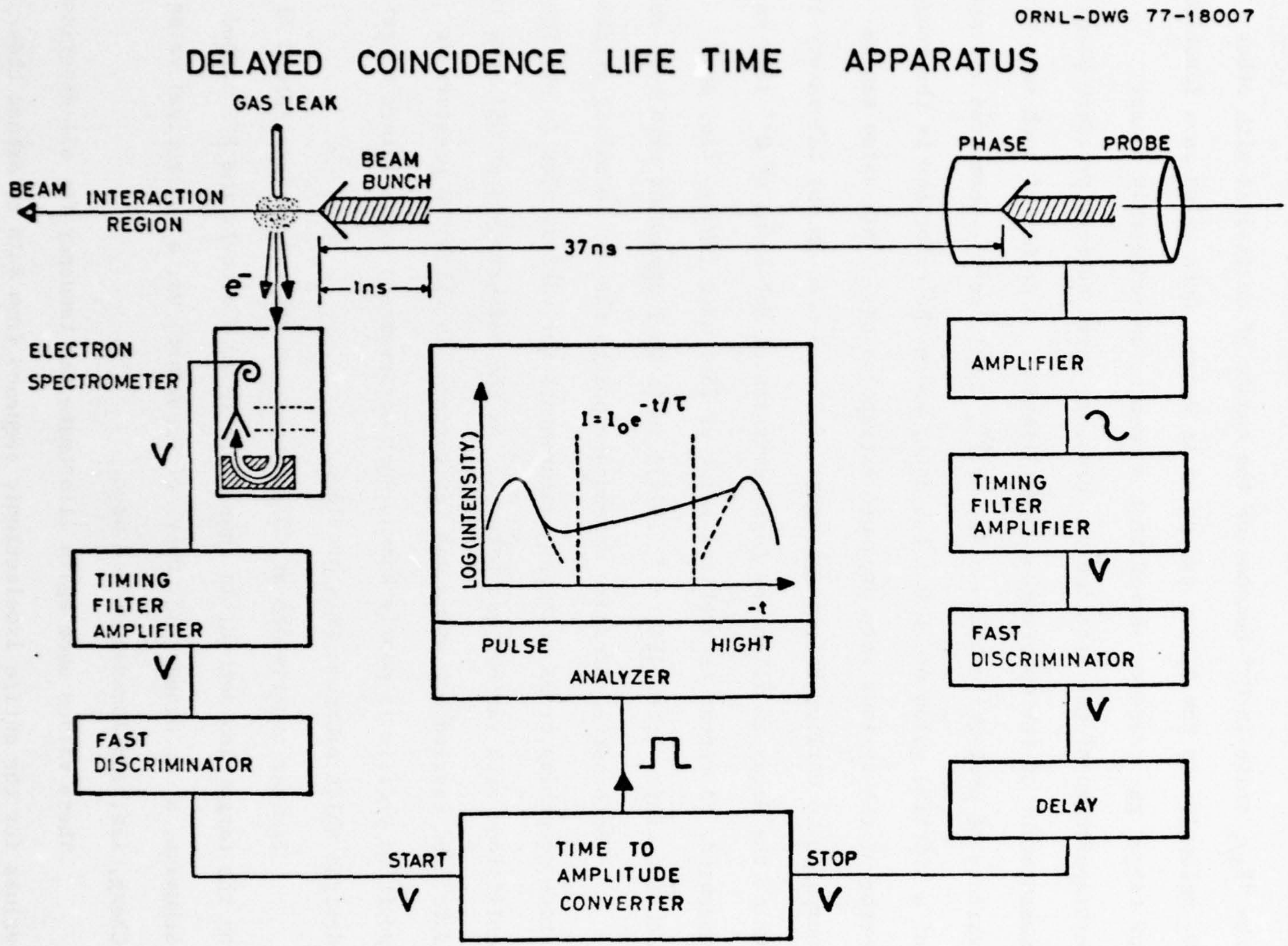
ORNL-DWG 77-18007
DELAYED COINCIDENCE LIFE TIME APPARATUS
GAS LEAK
BEAM
INTERACTION REGION
BEAM BUNCH
PHASE PROBE
37ns
1ns
e⁻
ELECTRON SPECTROMETER
AMPLIFIER
TIMING FILTER AMPLIFIER
FAST DISCRIMINATOR
DELAY
TIMING FILTER AMPLIFIER
FAST DISCRIMINATOR
I=I₀e^{-t/τ}
LOG(INTENSITY)
-t
PULSE HIGHT ANALYZER
START
STOP
TIME TO AMPLITUDE CONVERTER

Fig. 1

An example of such lifetime data is shown in Fig. 2. At the target pressure used, there is an appreciable collisional quenching effect on the $^4P_{5/2}$ state in O^{5+} because of the chance of collisions with other O_2 molecules in the target gas prior to decay. Data taken as a function of target gas pressure showed that a smooth, approximately linear extrapolation of the lifetime vs. pressure curve to zero pressure permitted measurement of the unperturbed state lifetime. A number of such runs with a variety of projectile ions--e.g., Ar^{12+}, Cu^{20+}, Kr^{26+}--permitted extraction of a lifetime value of 26.0 $\pm$ 1.5 nsec, where the error bar is the range error of the various zero pressure extrapolations. This value can be compared to earlier BFS measurements of 25 $\pm$ 3 nsec in our laboratory in which the decay in flight by Auger emission of MeV beams of O^{5+} ions was measured. A recent theoretical value of 23.1 nsec (Cheng, Lin, and Johnson, Phys. Lett. 48A, 437 (1974)) is in fair agreement with both results.

The observed pressure dependence points the way to making excited state quenching cross sections measurements for various slow ($\sim$ eV) ions in collisions with various gas targets. As the measurements at GSI have to date been carried out using gas jet targets, in which the pressure vs. position profile is poorly known, such measurements await future target designs which overcome this problem.

Similar experiments at GSI using Ne as the target gas yielded 11.2 nsec by the target ion method, in comparison to 10.4 nsec by the BFS method (S. Schumann, K. O. Groeneveld, Univ. of Frankfurt) vs. a theoretical value of Cheng, Lin, and Johnson of 8.4 nsec.

These values once again illustrate the tendency for all experimental values for the entire isoelectronic sequence from 8-18 to exceed those from theory by an average of 15%. Whether neglect of electron correlation in the calculations is responsible is still an unsettled question.

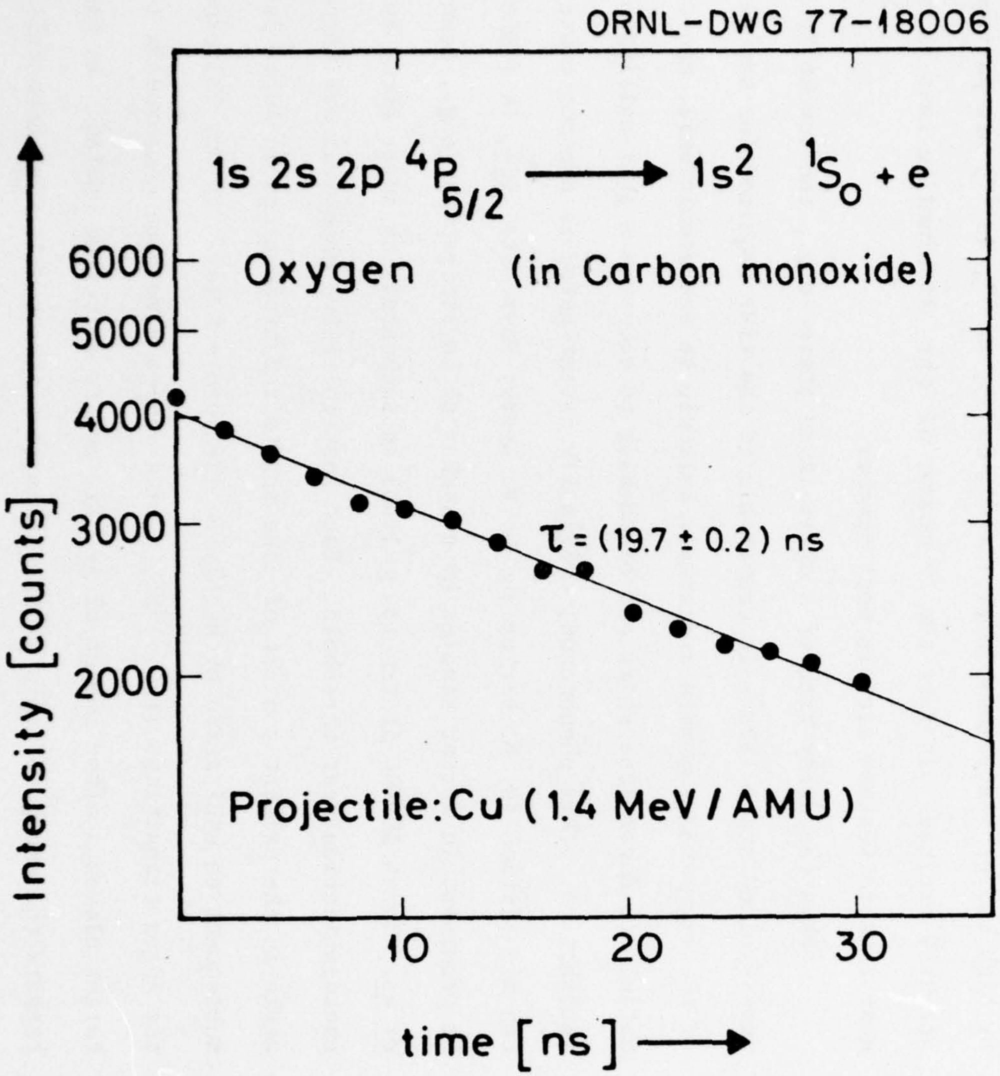
ORNL-DWG 77-18006
1s 2s 2p $^4P_{5/2}$ → 1s^2 $^1S_0$ + e
Oxygen (in Carbon monoxide)
τ = (19.7 ± 0.2) ns
Projectile: Cu (1.4 MeV / AMU)
Intensity [counts]
6000
5000
4000
3000
2000
10
20
30
time [ns]

Fig. 2

It is convenient to make Auger spectroscopy measurements on both the prompt and delayed transitions from both target and projectile systems using essentially the same apparatus, as has been done for the past few years by Mann, Groeneveld, et al. Auger lines of the core-excited lithiumlike charge states of light targets (e.g., Ne, O_2, CO) bombarded by high charge state ions (e.g., Ar^{12+}, Cu^{20+}, Kr^{26+}, Xe^{31+}) are particularly strongly excited. In fact the ^4P state of the lithiumlike ions is the most intense feature seen in most spectra.

When the decay time of a short-lived state--e.g., the lowest lying core-excited state $1s2s^2$--is comparable to the time required for the removal of the companion atom in a diatomic molecule to one atomic unit, one can anticipate Auger line shift and broadening to occur in a post-collision interaction. This phenomenon, originally investigated in another context in the mid-sixties (R. B. Barker and H. W. Berry, Phys. Rev. 151, 14 (1966)), is prominent in recent studies by a number of investigators (e.g., Schmidt, et al., Tenth ICPEAC Abstracts, p. 1068) in such areas as Auger decay following photoionization near threshold. Such post-collision phenomena are important again in the present context of line shifts and broadenings in Auger decay subsequent to excitation by highly ionized projectiles. In our GSI experiments, the Auger transitions $(1s2s^2)^2S_{1/2} \rightarrow (1s^2)^1S_0+e$ have been measured in light target elements after impact of Ar, Kr, and Xe ions from UNILAC. In monatomic targets the energy of this prompt transition agrees well with beam foil data and with Hartree Fock calculations. Transitions from target atoms in molecules like CH_4, however, are strongly shifted to lower energy and broadened in line width. A simple model to account for this effect in terms of Stark perturbation of the emitted electron by the neighboring ions is being worked out. It is possible that a sufficiently successful model will yield a method for determining lifetimes of short-lived Auger transitions, since the ratio of Auger decay time to separation time occurs directly in the model.

In the simplest version of the model the line is shifted from E_e to $E_e - \frac{1}{2}$ w, where the FWHM of the line is given by $\Delta E_{FWHM} = 1.07$ w, and

$$w\ (eV) = q_p \sqrt{m_p/E_p}\ (3.3 \times 10^{-15}/T),$$

where q_p is the projectile charge, E_p the projectile energy in keV, m_p the projectile mass in amu, and T the lifetime of the excited Auger level. Since the Li-like ^4P levels are long-lived, it is convenient to express the shifts and widths of the ^2S line with respect to the ^4P lines. In CH_4, for example, the interval $E(^4P) - E(^2S)$ is measured to be 5.2 ± 2 eV, and the line width 3.9 ± 1 eV. The estimated width $\Delta E_{FWHM} \cong 1.07$ w is 3.5 eV, if one assumes a lifetime $\sim 5 \times 10^{-15}$ sec. For other lifetimes, ΔE_{FWHM} scale as $5 \times 10^{-15}/T$. Data from the Ph.D. thesis of Mann exist for CH_4, NH_3, N_2, CO_2, and CO_2 targets. The collaborative work discussed here concerns improved measurements on CH_4 and NH_3.

A third type of experiment begun collaboratively at GSI and presently continuing is the measurement of the projectile charge state dependence of the strength of various target atom Auger lines, particularly the strongly excited lithiumlike ion lines. There is both theoretical impetus and experimental advantage in undertaking such measurements at this time. First, in a recent paper of C. Bottcher (J. Phys. B. Lett. 10, L445 (1977)) entitled "Many-electron Stripping in Collisions Between Atoms and Heavy Ions," a number of interesting predictions concerning multiple electron ejection from light target atoms are made (cf. the discussion beginning Section C.1). Among these are: (1) that the dominant process for multiple target electron ejection is into continuum states entered on the projectile (i.e., electron transfer into projectile continuum states); (2) the cross-sections for removal of most, if not all, of the target electrons in a single step process are remarkably large (i.e., often larger than geometrical for the K shell of the target system); (3) the limiting cross-sections are those for one- and two-K electron removal, with other accompanying target excitations or ionizations modulated by these primary processes; and (4) there is strong structure in, for example, the cross-section for simultaneous 10-electron removal from neon (or other atoms) both as (a) a function of collision velocity and of (b) effective screened projectile charge state. Our experiment at GSI concerns predictions 3 and 4(b). On the assumption (3) that both the production of the lithiumlike $(1s2s2p)^4P$ state and the ten electron removal cross section are modulated by similar K-electron cross sections then such structure should also appear in the excitation function for this state. There is a pronounced peak at $Z_{EFF} = 10$ in the 10 electron removal cross-section. By using magnetic selection of charge states near 10 created by equilibrating Ar^{12+} beams at 1.4 MeV/nucleon in C foils, it is possible to study the charge state dependence of 7 electron removal (including 1 K electron) through studying the excitation function of the most prominently excited state in the Auger spectrum, the $1s2s2p\ ^4P$ state. An additional significant advantage of studying this Auger decay channel is that its fluorescence yield is unity. Avoiding the need to understand the rapid charge state variations of x-ray decay channel fluorescence yields is a critical advantage. Preliminary data from this experiment obtained in a run in early September does not display the predicted charge state dependence--but at the moment, the scatter in the data due to geometric problems associated with gas jet density variations does not rule out the theoretical predictions. Experimental target improvements are currently under way. Future experiments concerning predictions (1) to (4) are planned for the coming year at both ORNL and GSI, as indicated in Section D.1 of this proposal.

C.2. Lifetimes of Intra-Shell ($\Delta n = 0$) Transitions in $n = 2$ and 3 Levels of Simple, Highly Ionized Ions

The effort to develop an xuv spectrometer arrangement suitable for making lifetime measurements on many ions in intermediate stages of ionization--with emphasis on the resonance transitions, in many of which the principal quantum number remains unchanged--began with ONR support in 1973. The present apparatus is depicted in Figs. 3 and 4. Gradual improvement and development of this apparatus with the help of P. M. Griffin (ORNL) and R. Laubert (NYU) has culminated during the past contract year and the present one in the publication of a large number of results on many $\Delta n = 0$ resonance transitions of lithiumlike, berylliumlike, boronlike, carbonlike, nitrogenlike, sodiumlike, and magnesiumlike configurations of a number of different elements. We call attention to papers A16, A17, A21, A22, A29, A30, A31, A32, A42, A43, A44, A45, A46, A49, A50, B7, B12, B14, B28, B29, and B30, which contain by title a fairly complete list of ions and transitions therein studied at ORNL. In this work we have enjoyed the collaboration of a number of colleagues at other institutions, as noted in the Section on Personnel. In addition, we have collaborated with more of these colleagues in similar experiments at the Brookhaven National Laboratory and at the Berkeley HILAC accelerator as noted in papers A9, A15, A27, A28,

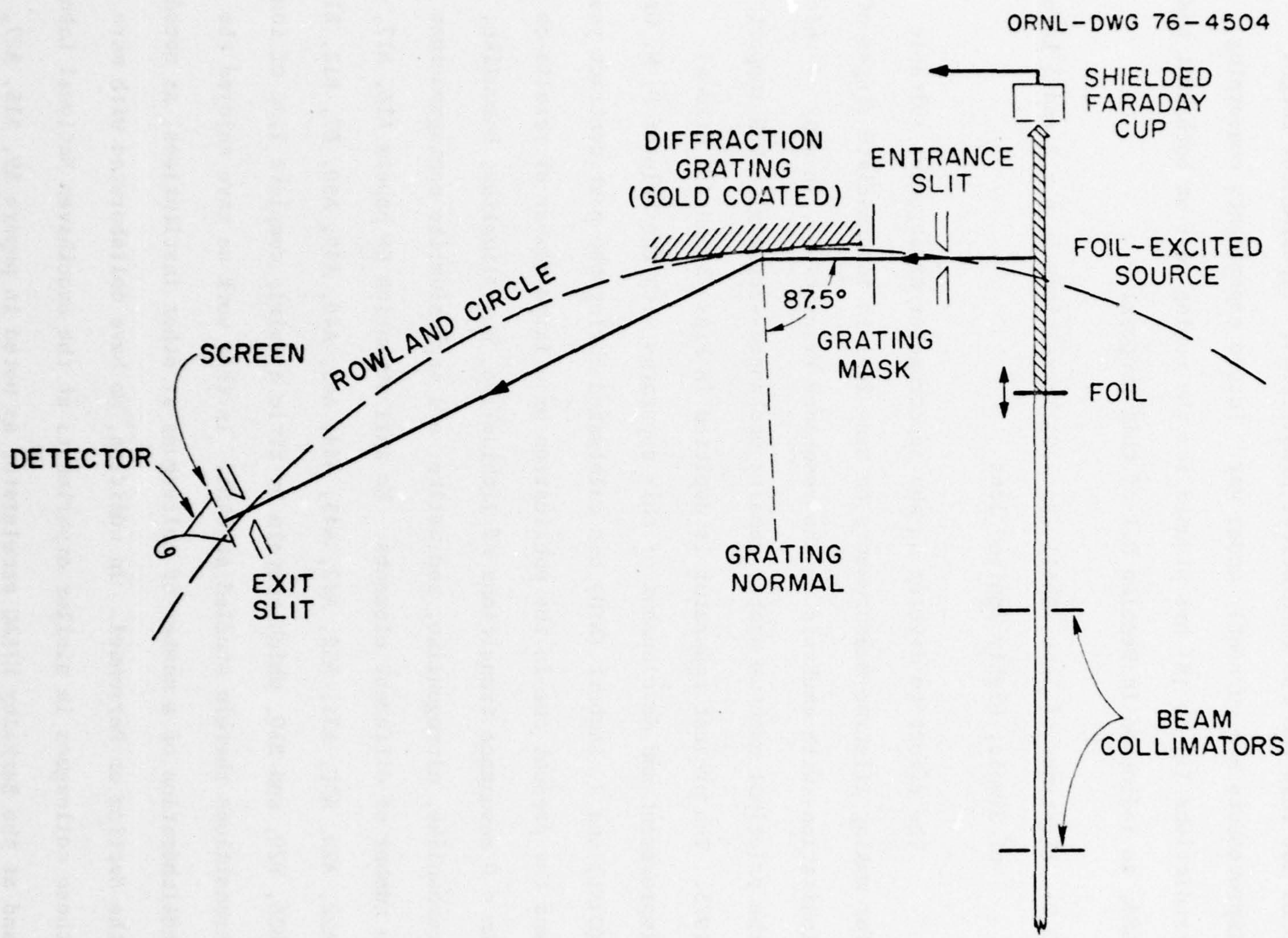
ORNL-DWG 76-4504
SHIELDED FARADAY CUP
DIFFRACTION GRATING (GOLD COATED)
ENTRANCE SLIT
FOIL-EXCITED SOURCE
87.5°
GRATING MASK
FOIL
ROWLAND CIRCLE
SCREEN
DETECTOR
EXIT SLIT
GRATING NORMAL
BEAM COLLIMATORS

Fig. 3

ORNL-DWG 77-5332

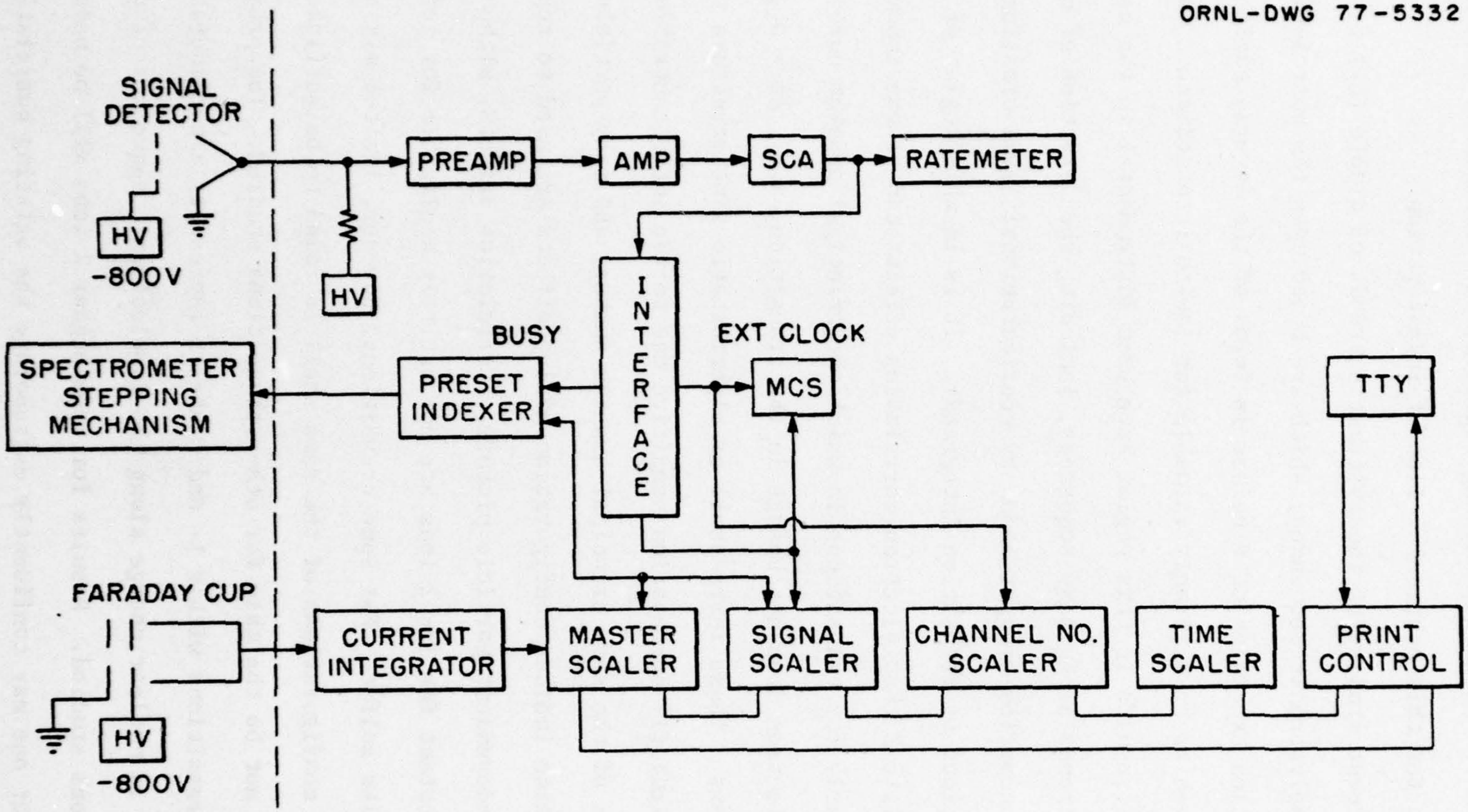

Fig. 4

A41, and A47. Before discussing representative results we comment on the rationale for this particular line of investigation.

Recent studies of the systematic trends of dipole (E1) f-values along isoelectronic sequences, which are based upon the nonrelativistic perturbation expansion of f-values in terms of the inverse nuclear charge, have proven to be extremely valuable for low-to-intermediate Z ions. Our beam-foil results in this region have been instrumental in the establishment of such trends along many sequences, including the detection of certain f-value anomalies brought about by configurational level crossings or cancellations of transition integrands. It is in this region of low-to-intermediate Z that electron correlation effects can become important, particularly for transitions in which the principal quantum number of the active electron does not change in the transition, i.e., $\Delta n = 0$ (intra-shell). transitions. These intra-shell or electrostatic fine structure transitions are particularly correlation sensitive due to the interpenetration of the electrons of the same principal quantum number, and many-particle atomic models which include configuration mixing effects are used to replace the simple independent particle picture. Correlation effects, although usually most important for low Z ions are not entirely negligible for intermediate Z ions like sulfur. For some transitions, however, limited mixing with adjacent configurations of the same shell is found to be sufficient, but this may not be the case for other transitions studied. The present work on $\Delta n = 0$ transitions within L- and M-shells represents a considerable extrapolation in nuclear charge along the isoelectronic sequences of all the transitions studied. Results for even higher Z ions will be necessary in order that one may confidently extrapolate the existing nonrelativistic systematic curves into the very high Z region where relativistic effects on f-values, such as orbital shrinkage and configurational effects involving the breakdown of the LS coupling scheme become appreciable. Recent relativistic f-value calculations by Kim and Desclaux, [Phys. Rev. Lett. 36, 129 (1976)], Weiss [in Beam-Foil Spectroscopy, Vol. I (Plenum Press, N.Y., 1976)], and Lin and Armstrong [Phys. Rev. A14, 1114 (1976)] indicate that in the cases of the Li- and Be-sequence for example, the calculated f-values for the resonance lines begin to significantly depart from the nonrelativistic value around $Z \sim 25$. In fact it is the transition energies which deviate from nonrelativistic values in this region of Z and not the line strengths. A selected number of experimental beam-foil results in this uncharted relativistic regime could greatly serve to guide theoretical progress. In fact, our recent investigation of lithiumlike S provides a measured verification of such a relativistic effect on the $2s\text{-}2p_{1/2,3/2}$ transition rates. Our measurements on sodiumlike Cu also verify relativistic calculations.

Comparisons of accurately measured electric dipole transition probabilities of f-values with calculations of such quantities afford sensitive tests of the correctness of the wavefunctions used in the upper and lower states of the transition. Two distinct types of allowed radiative processes can be distinguished. "Out-of-shell," inter-shell or $\Delta n \neq 0$ transitions, whose rates scale as Z^4 along an isoelectronic sequence and $\Delta n = 0$ electrostatic fine structure transitions which scale linearly with Z. The $\Delta n \neq 0$ transitions become too rapid for the beam-foil time-of-flight method for large Z, low N ions (N = number of electrons), but $\Delta n = 0$ transitions remain accessible to beam-foil studies to surprisingly high Z because of the considerably weaker Z-scaling dependence. It is these

$\Delta n = 0$ transitions of the type $2s^22p^k$ - $2s2p^{k+1}$ and $2p^k$ - $2p^{k+1}$ within the L shell, and their analogs in the M-shell that are studied in the present work. As an example, Fig. 5 shows a partial energy level diagram of the n = 2 manifold of states associated with the berylliumlike ion, S^{12+} to illustrate this type of transition. We have measured the transition probabilities for all of the decay channels shown.

The motives behind our work stem from practical needs as well as fundamental reasons. For example, one of the current problems in the physics of magnetically confined thermonuclear plasmas is to estimate the radiative energy losses due to dipole radiative transitions in highly stripped impurity heavy ions known to be present in the plasmas. Such energy dissipation can contribute appreciably to the unwanted cooling of the plasma. Primarily because of the urgent need for relevant oscillator strengths for these $\Delta n = 0$ resonance transitions within the L, M, and N shells of highly ionized impurity heavy ions, theorists are currently attempting to make relativistic calculations of such quantities.

Details of the apparatus and measurement procedures were adequately discussed in our renewal proposal of one year ago. We concentrate instead on a description of representative recent results, with emphasis on results obtained in the last contract year.

In general the measured lifetimes are longer than predicted by current theory by up to 40%. Of course, transition probabilities, where derivable, are lower than corresponding theoretical predictions by the same amount. Since cascading and/or blending do not in general appear to be a major problem in the present experiments, it is suspected that insufficient mixing effects have been taken into account in the multi-configurational calculations. In cases such as the $(2s2p)^3P^o$ - $(2p^2)^3P$ transition in the Be-sequence (S^{12+}),

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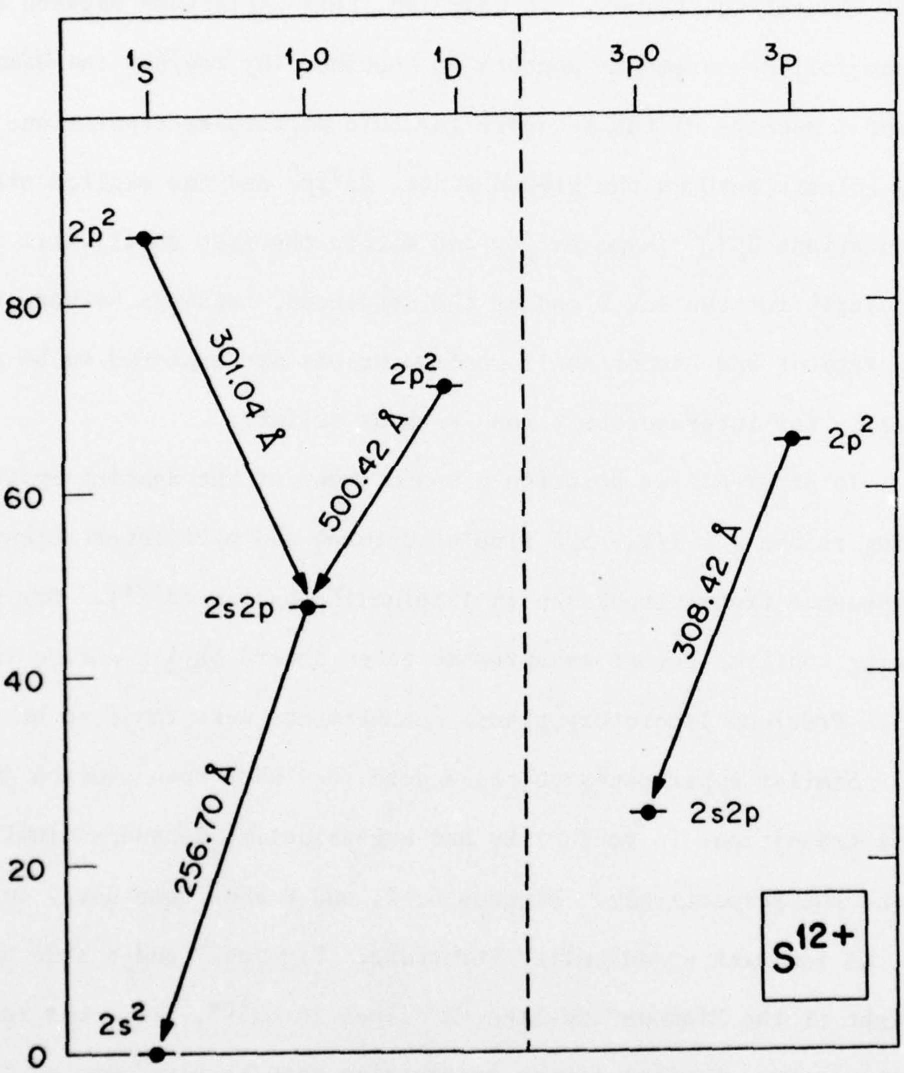


Fig. 5

where configuration mixing is expected to be very small, there exists excellent agreement between theory and the present result. In contrast, however, the measured transition probability for the $(2s^22p)^2P^o$ - $(2s2p^2)^2P$ transition in the B-sequence (S^{11+}) is found to be $\sim$ 40% lower than the current theoretical values. In addition, this difference between theory and beam-foil measurements appears to continue, by roughly the same amount, to lower Z members of the sequence for this particular transition. Strong mixing effects between the ground state, $2s^22p^n$ and the excited state configurations $2p^{n+2}$ (same parity and within the same shell) will occur, particularly for the low Z end of the sequences. Mixings between L-shell configurations and higher shell configurations are expected to be small, especially for intermediate Z ions such as sulfur.

In paper A17 we describe a measurement of the doublet splitting (leading to the J = 1/2 - 3/2 fine structure) and oscillator strengths for the resonance transition 2s-2p in lithiumlike sulfur (S^{13+}). Our energy splitting confirms recent measurement taken aboard Skylab during solar flare events. Previous laboratory plasma measurements were found to be in error.

Similar experiments to those described have been made on $\Delta n = 0$ M shell transitions in sodiumlike and magnesiumlike Fe, and sodiumlike Cu at ORNL and BNL, respectively. Figures 6, 7, and 8 show some decay curves for Cu^{18+}, an ion with a sodiumlike structure. Figures 7 and 8 show the decay in flight of the "famous" Na-like "D" lines in Cu^{18+}, i.e., the resonance doublet, 3s-3p. Several rather interesting results have come out of this experiment. First, an unusually strong cascade fall was observed on all the decay curves. Data was taken out to more than ten decay lengths of the primary level in order to investigate this long-lived component. If the data had been analyzed out to only three decay lengths, as is usual in

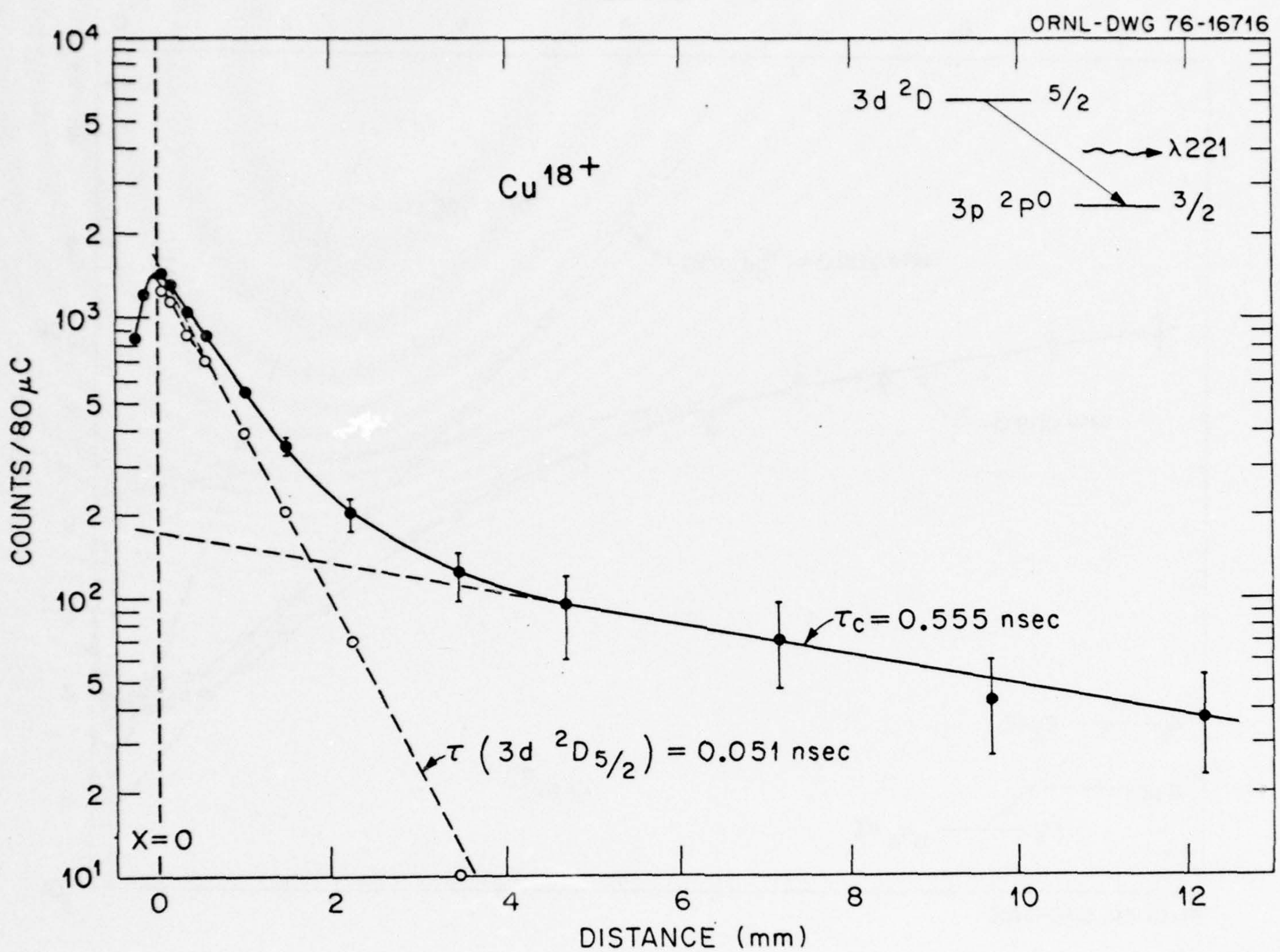
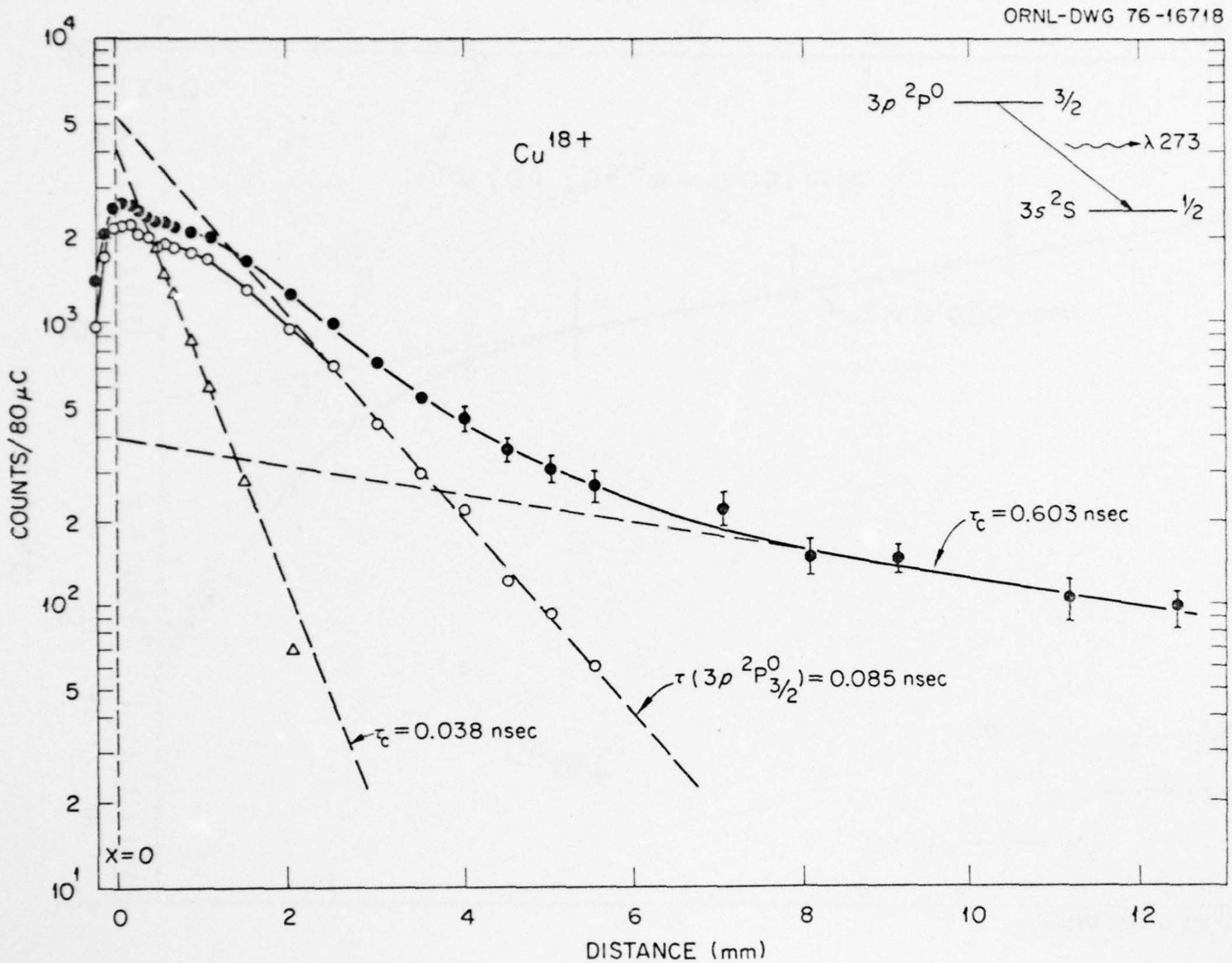

ORNL-DWG 76-16716
Cu18+
3d 2D 5/2
λ221
3p 2P0 3/2
τc = 0.555 nsec
τ (3d 2D5/2) = 0.051 nsec
X=0
COUNTS/80 μC
DISTANCE (mm)
10^4
5
2
10^3
5
2
10^2
5
2
10^1
0
2
4
6
8
10
12

Fig. 6



ORNL-DWG 76-16718
Cu^{18+}
$3p\ ^2P^0$ — 3/2
λ273
$3s\ ^2S$ — 1/2
$\tau_c = 0.603$ nsec
$\tau(3p\ ^2P^0_{3/2}) = 0.085$ nsec
$\tau_c = 0.038$ nsec
X=0
COUNTS/80μC
DISTANCE (mm)

Fig. 7

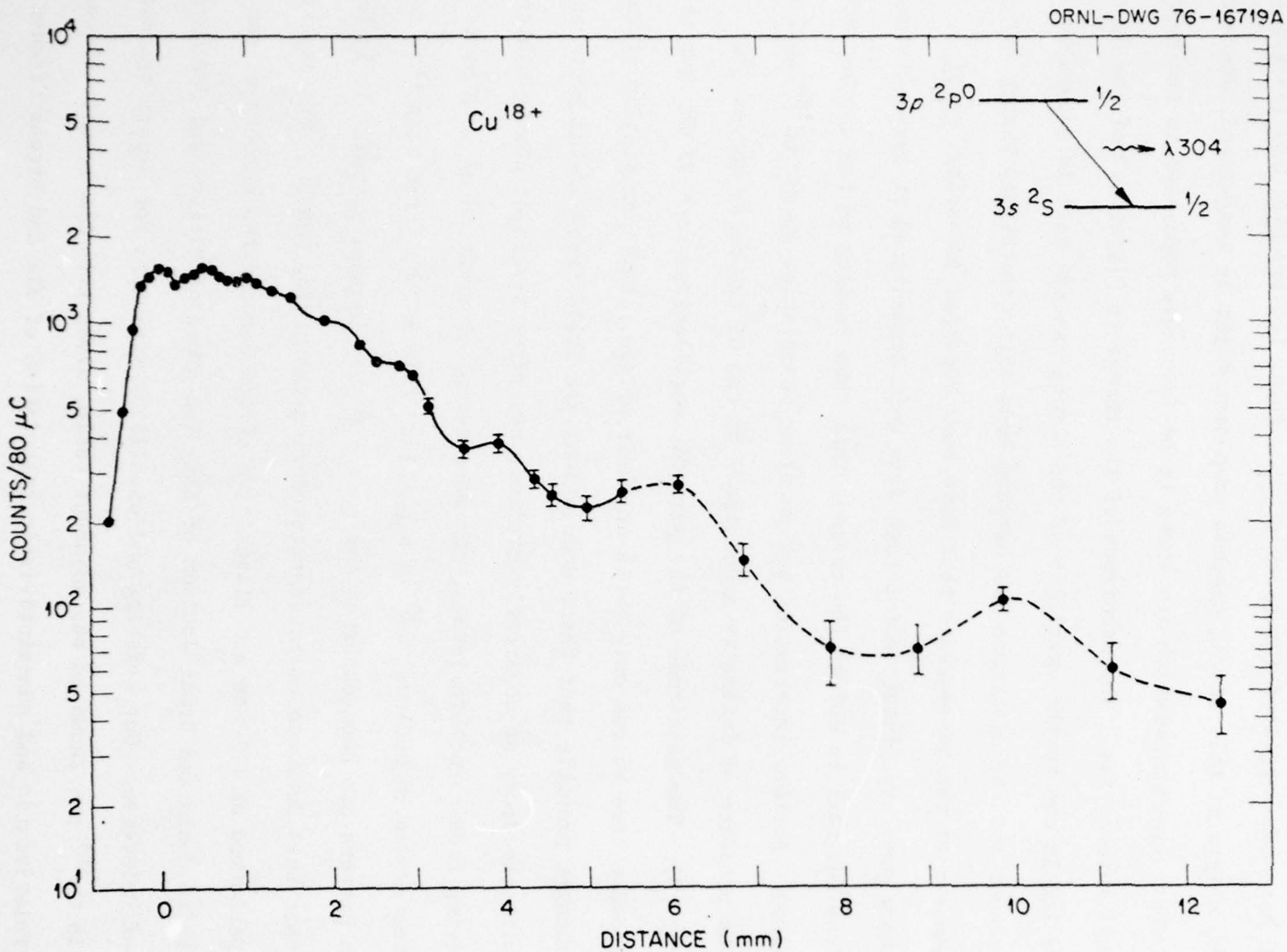

ORNL-DWG 76-16719A
Cu 18+
3p 2P0 1/2
λ304
3s 2S 1/2
COUNTS/80 μC
10 4
5
2
10 3
5
2
10 2
5
2
10 1
0
2
4
6
8
10
12
DISTANCE (mm)

Fig. 8

beam-foil measurements, the "lifetime" results would be some 40% too high! It has been suggested (Crossley et al., Phys. Letters 57A, 220 (1976)] that the origin of this strong cascade component might be long-lived, unbranched Rydberg-type states which are known to be favorably populated in the beam-foil interaction. The magnitude of the change in "lifetime" of the 3p and 3d levels due to the existence of the strong cascade tail is enough to account for the discrepancies between beam-foil results and theory for other members of the Na-sequence that have been reported (Crossley, et al.). In these past experiments not enough data were accumulated at large distances from the foil to define the cascade tail thus leading to the discrepancies cited. Another interesting but puzzling observation in our Cu^{18+} work was the presence of intensity modulations on two of the decay curves (see Fig. 8). The magnitude of the periodic oscillations is $\sim$ 25 GHz but at the present time we can only guess at their origin. While originally it was thought probable that these modulations are field-free quantum beats associated with the decay of coherently-excited, hyperfine levels or possible high lying fine-structure levels, our more recent observation of such beats in the even-even nucleus Ni^{58} is a puzzle. This is the first time that such a pattern has been observed for such a highly ionized system. It is hoped that this data can be interpreted during the coming months. The experiment, performed at BNL was a collaborative effort between two members of our group, Keith Jones and Brant Johnson of BNL, Ted Kruse of Rutgers and Joe Cecchi of Princeton. Our lifetime and oscillator strengths for dipole transitions in Cu^{18+} are shown in the adjacent table, along with the results of recent relativistic and nonrelativistic calculation of Kim and Froese-Fischer respectively. Again, as in the case of the Li-sequence, it can be seen that the line strength factor is not affected appreciably by relativity for

Table II. Radiative Lifetimes and Dipole Oscillator Strengths in Cu^{18+}.

Wavelength (Å)	Transition	Lifetime of Upper level (psec)	Oscillator Strength Present	Oscillator Strength Theory*
303.5	$3s\,^2S_{1/2} - 3p\,^2P^{\circ}_{1/2}$	85±18	0.16	0.12[a],0.11[b]
273.3	$3s\,^2S_{1/2} - 3p\,^2P^{\circ}_{3/2}$	85±9	0.26	0.25[a],0.24[b]
207.3	$3p\,^2P^{\circ}_{1/2} - 3d\,^2D_{3/2}$	54±6	0.24	
221.4	$3p\,^2P^{\circ}_{3/2} - 3d\,^2D_{5/2}$	51±5	0.22	

*Values based upon calculated line strengths and experimental transition energies.

[a]Reference 2 (Relativistic line strengths).

[b]Reference 3 (Nonrelativistic line strengths with core-polarization).

Z = 29, but the transition energy has significantly changed due to the break-down of the LS coupling scheme.

In general, it can be said that our extensive experimental results are in excellent accord with recent theory, at least when the theoretical results have explicitly incorporated sufficient configuration interaction and relativistic energy splitting effects in cases where these are important. A rare exception is the $2s^2\ ^1S$ - $2s2p\ ^1P^o$ transition in berylliumlike ions. There is a systematic tendency for all oscillator strengths from BFS measurements (the ones for Cl^{12+} and S^{12+} are those from our laboratory at ORNL) to underestimate theoretical f-values, except for Be itself. The reason is that two principal feeding transitions, $2s2p\ ^1P^o$ - $2p^2\ ^1D,{}^1S$ have f-values comparable to each other as well as to the transition of interest, leading to severe though somewhat accidental problems in disentangling the cascade feeds, even though these are separately measured in the same experiments. Only for neutral Be, where the $2p^2$ state is thought to lie in the autoionization continuum, does one accept this problem. For the cascade feeds themselves good agreement between experiment and theory exists.

In view of the extensive improvement in the experimental and theoretical situation in the past two years, it thus becomes logical to shift emphasis more in the direction of studying more poorly understood collision phenomena which govern populations of these highly ionized and excited states. In Section D, several future projects with this general aim are proposed.

C.3. Collisional Production and Electron Spectroscopy of Core-Excited States of the Alkali Metals and Alkali-like Ions

Since our renewal proposal of one year ago (see Section C.4 of last year's proposal/annual update) we have collected a substantial quantity of data in an investigation of the production of core-excited states of lithium in single collisions with various gas targets over an impact energy range from 10 to 50 keV. Some of these results have been presented in contributed papers at recent conferences (A10, A26, and A39) and we expect further analysis to lead to a formal publication shortly. This work was accomplished using our large cylindrical mirror analyzer and the 50 keV ion accelerator originally designed for these studies.

Figure 9 shows the autoionization electron spectra observed at a laboratory frame observation angle of 42.3 degrees for collisions of 50 keV Li^+ ions with several noble gas targets. The evident variation of relative line intensities and widths with target species reflects the specific nature of the excitation, which is believed to be the result of molecular orbital promotion processes. For collisions involving the heavier noble gases (argon and krypton), excitation of doubly core-excited (helium-like) Li^+ is observed in relatively large quantity, as shown in Fig. 10.

Relative line intensities are observed to vary with impact energy as well as with target species. A particularly interesting example occurs in the $(Li\text{-}He)^+$ collision system, and is illustrated in Fig. 11, which exhibits the yield of lithium autoionization electrons associated with particular lines in the spectrum as a function of projectile energy. A simple kinematic analysis shows that the relevant (projectile frame) observation angle varies only slightly from the "magic" angle of 54.7 degrees for these data, so we believe our results are only slightly affected by angular distribution effects due to possible collisionally-induced alignment. The group at the Hahn-Meitner Institute (Berlin) have published data suggesting that the excitation mechanism for these states involves a double ($2p\sigma$-$2p\pi$) rotational coupling and a subsequent core-excitation caused by a ($1s\sigma$-$2p\sigma$) radial coupling. Our considerably more detailed results confirm and extend this suggestion. Since the rotational and radial couplings in this system are significant at very small and moderate, respectively, internuclear distances, we have assumed the couplings to be incoherent, and have plotted in Fig. 11 the projectile-velocity dependent product of a suitably-scaled cross-section for double rotational coupling (σ_2) obtained from the work of Taulbjerg, Briggs, and Vaaben and a radial coupling transition probability (w) calculated following the technique of Meyerhof and based on the Demkov charge-transfer model. At this time, the absolute detection efficiency of our apparatus is not accurately known, so we have arbitrarily normalized the quantity $w\sigma_2$ in the figure to permit comparison with the velocity dependence of the sum of lithium core-excited yields. We are encouraged by the velocity dependence agreement between $w\sigma_2$ and the total lithium yield, and are presently exploring secondary mechanisms involving further rotational couplings at larger internuclear separations and spin-exchange effects to understand how the excitation described above (which in a naive model would populate only $Li(1s2p^2)^2D$) is shared with other exit channels. Of special interest is the strikingly different behavior of the $1s(2s2p\ ^1P)^2P$ and $1s(2s2p\ ^3P)^2P$ excitation functions. Since these states have the same electronic configuration, and because the nature of the primary excitation mechanism requires that the molecular orbitals correlating with the lithium L shell form spin singlets, it is not possible to explain this behavior in terms of single-configuration models.

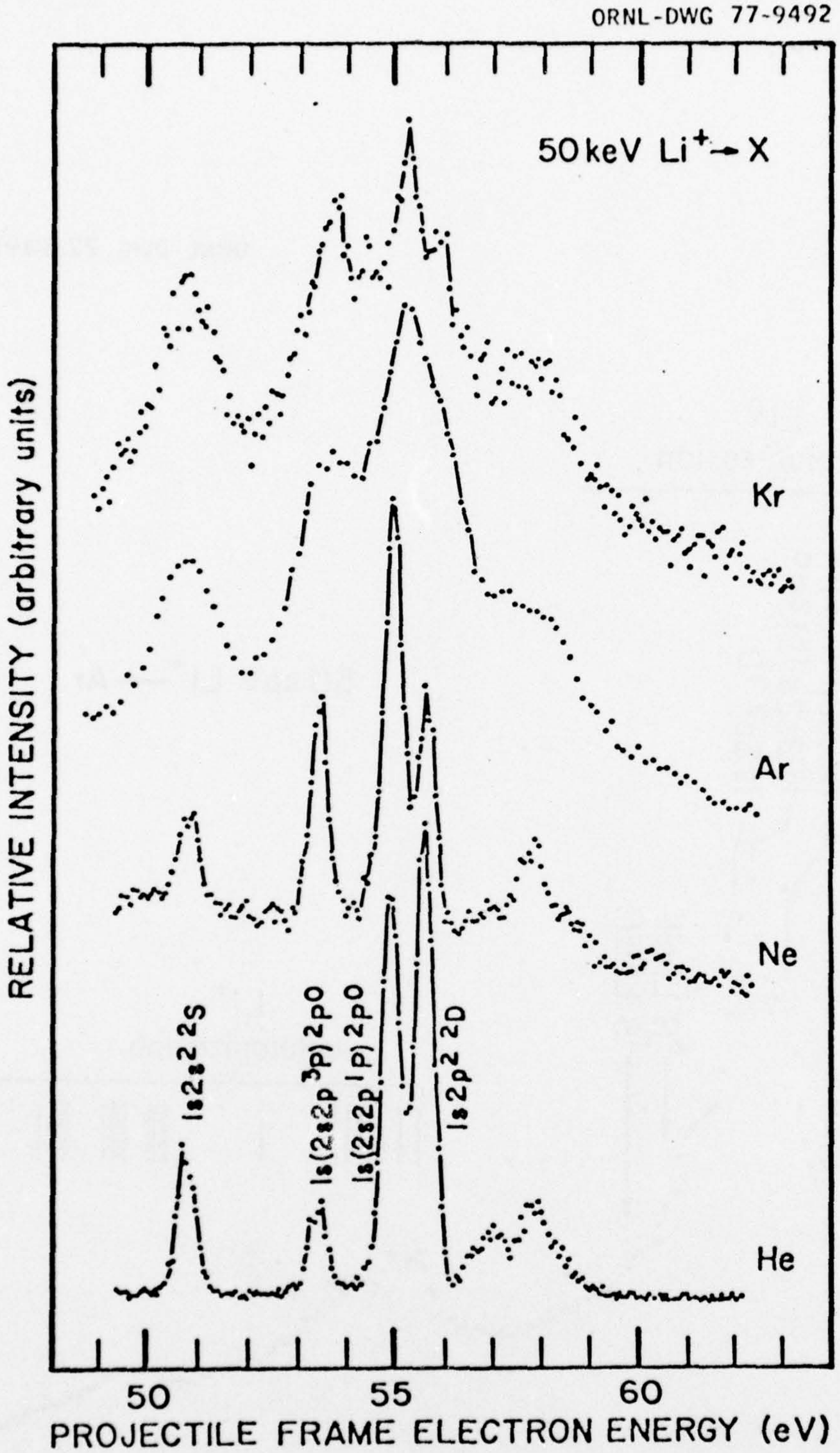


Fig. 9. The variation of relative line intensities and widths of autoionization electrons from core-excited states of lithium produced in 50 keV single collisions with noble gas targets. The vertical scale of each spectrum has been arbitrarily scaled to permit comparison.

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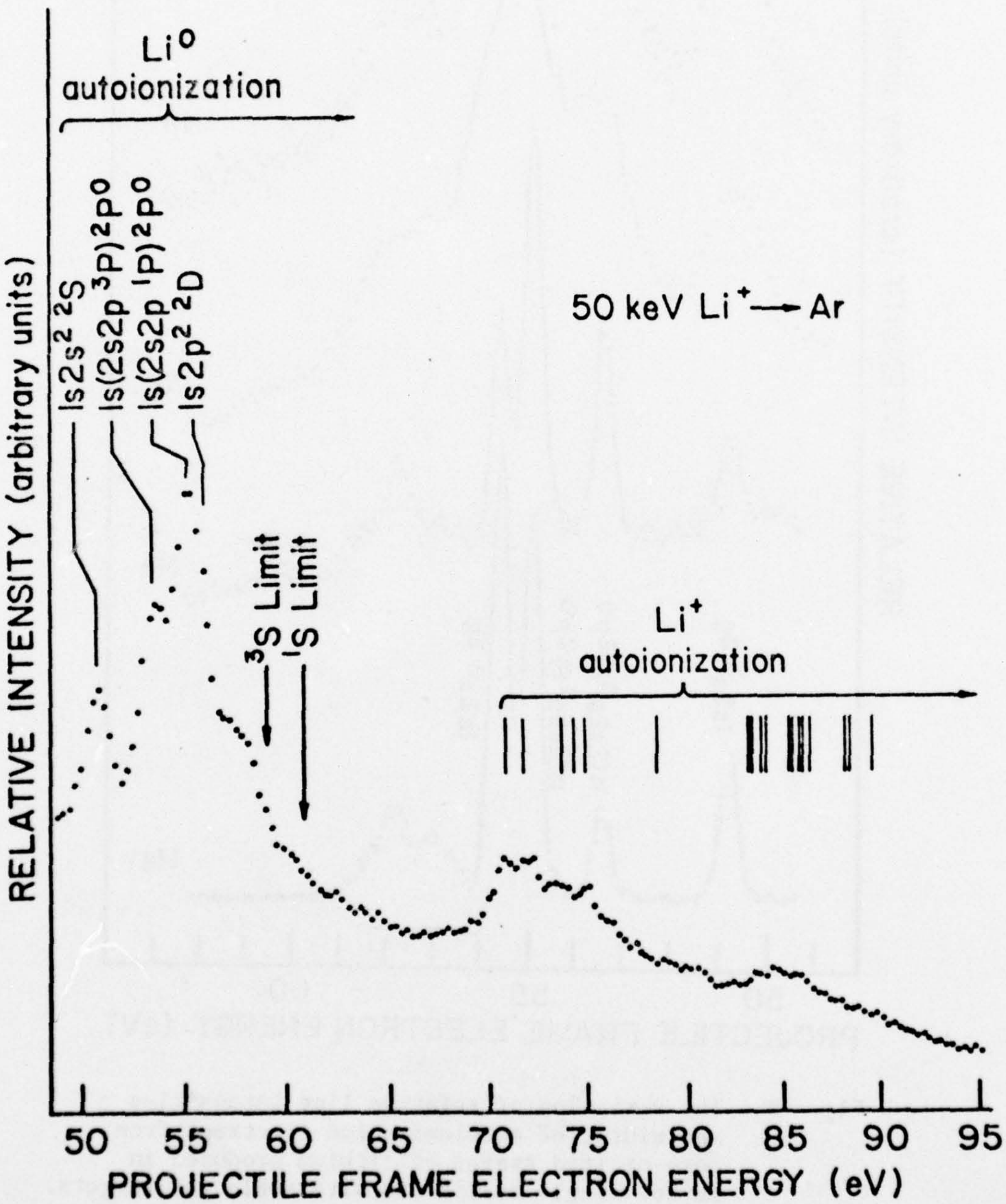

Fig. 10. The spectrum of autoionization electrons emitted by 50 keV lithium projectiles after single collisions with an argon target.

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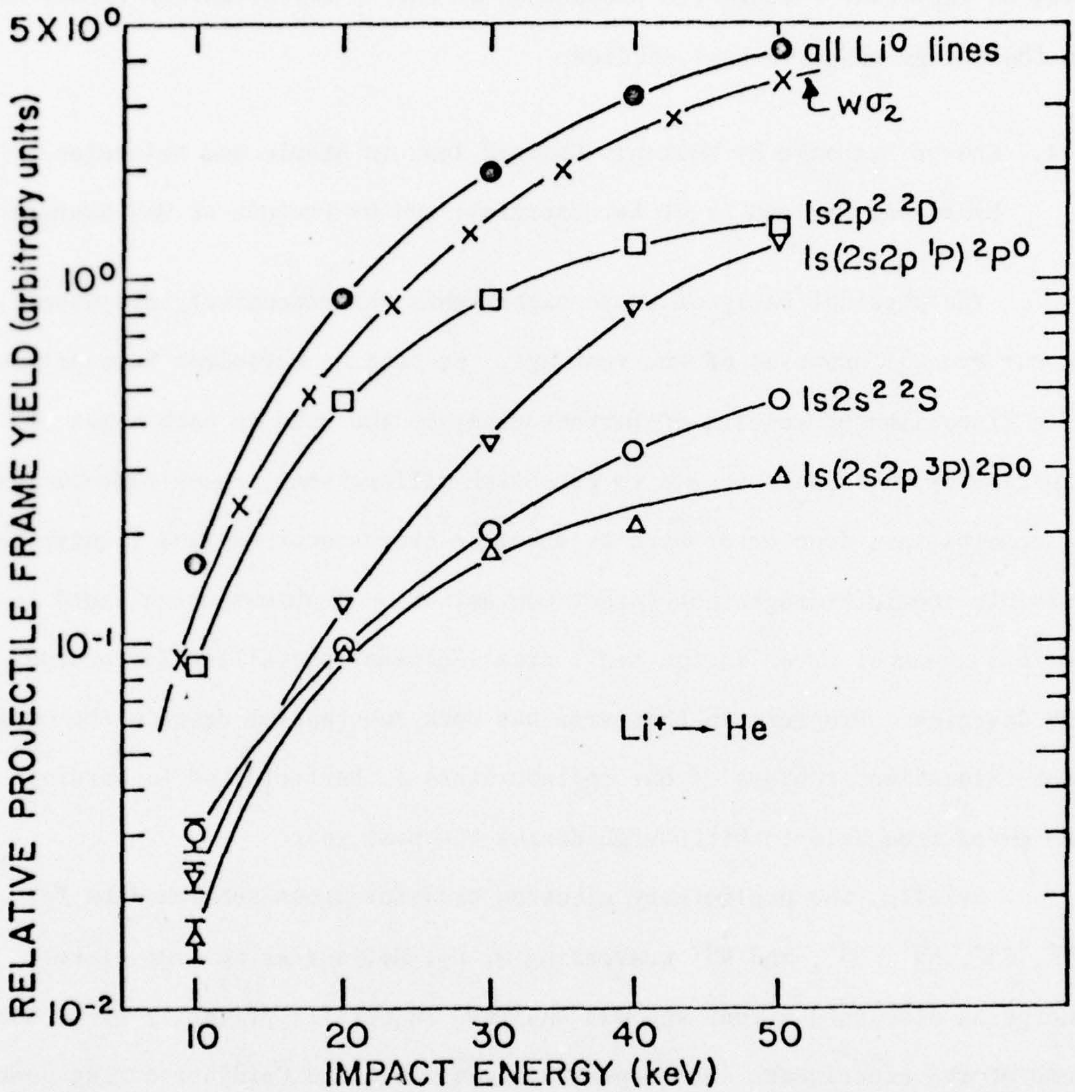


Fig. 11. Relative excitation functions for the four major lines and the sum of all lines in the autoionization spectrum of neutral lithium, produced in single collisions with helium. Also plotted is the quantity $w\sigma_2$, discussed in the text, which is calculated on the assumption of a specific primary excitation mechanism, and to which has been applied an arbitrary overall normalization.

Accordingly, we suspect that spin-exchange and configuration interaction effects play an important role in the production of the ^2P states in the $(LiHe)^+$ system in the energy range we have studied.

C.4. Charge Exchange by Multiply Charged Ions in Atomic and Molecular Hydrogen, He, and Ar at keV Energies; and by Protons at MeV Energies

The physical basis of these experiments was extensively discussed in our renewal proposal of one year ago. We confine ourselves here primarily to a discussion of results of further analysis and runs on both types of experiments whose purpose was to establish calibrations, check reproducibility of results, pin down error bars on absolute cross-sections, and inquire into possible atomic hydrogen hot target contamination problems which could be serious causes of error in the small cross-sections prevailing for protons at MeV energies. Progress in this area has been substantial despite the equipment relocation problems of our collaborators J. Bayfield and L. Gardiner who moved from Yale to Pittsburgh during the past year.

Briefly, the preliminary electron transfer cross section data for B^{q+}, C^{q+}, N^{q+}, O^{q+}, and F^{q+} traversing H, H_2, He, and Ar at tens of keV energy as discussed a year ago was analyzed in detail, primarily by L. Gardiner. Some of the experiments were repeated by Bayfield and Gardiner during June of this year. Some downward revision of the preliminary data occurred in this process, partially as a result of a discovery that the ORNL Penning ion source used for the work intermittently puts out a $\sim$ 50 hHz pulsed beam with a duty cycle of $\sim$ 0.02, leading to large detector dead time connections when this occurs. A table of interim results from L. D. Gardiner's thesis accompanies this discussion. When written up for publication, submission of these results to Phys. Rev. A is contemplated. Single electron transfer cross-sections are given in this table in units of 10^{-15} cm^2 at the beam energies indicated.

TABLE III.

Reaction	keV	Present Data	Reaction	keV	Present Data
B^{2+} + H	16	31 ± 8	N^{3+} + H	24	36 ± 13
+ He		0.44 ± 0.09	+ He		4.6 ± 1.7
+ H_2		22 ± 4	+ Ar		9.0 ± 1.8
+ Ar		26 ± 5			
			N^{4+} + H	32	46 ± 18
B^{3+} + H	24	12 ± 4	+ He		1.5 ± 0.6
+ He		12 ± 4	+ Ar		31 ± 11
+ H_2		7.5 ± 1.6			
+ Ar		8.2 ± 1.6	N^{5+} + H	40	56 ± 20
			+ He		10.6 ± 3.5
B^{4+} + H	32	38 ± 11	+ Ar		26 ± 5
+ He		4.0 ± 1.2			
+ H_2		19.6 ± 5.9	O^{2+} + H	16	2.2 ± 1.0
+ Ar		30 ± 8	+ He		6.2 ± 1.7
			+ H_2		1.6 ± 0.4
C^{2+} + H	16	6.5 ± 2.6	+ Ar		4.0 ± 1.1
+ He		3.2 ± 0.9			
+ H_2		10.2 ± 2.8	O^{3+} + H	24	61 ± 21
+ Ar		7.5 ± 2.1	+ He		2.6 ± 0.5
			+ Ar		14.8 ± 3.0
C^{3+} + H	24	17.7 ± 6.1			
+ He		14.1 ± 4.0	O^{4+} + H	32	50 ± 17
+ Ar		7.3 ± 1.8	+ He		7.9 ± 1.8
			+ Ar		31 ± 6
C^{4+} + H	32	50 ± 12			
+ He		1.87 ± 0.55	O^{5+} + H	40	65 ± 24
+ H_2		23 ± 5	+ He		17.5 ± 6.0
+ Ar		28 ± 6	+ Ar		26 ± 7
N^{2+} + H	16	4.2 ± 1.8	O^{6+} + He	48	10.4 ± 2.8
+ He		5.3 ± 1.5	+ Ar		50 ± 14
+ H_2		3.1 ± 1.0			
+ Ar		5.5 ± 1.8	$^3He^{++}$ + H	16	15.4 ± 3.1

A study of reproducibility due to possible contaminant problems in our MeV p on H charge exchange experiments revealed sufficient scatter in cross section data obtained at energies above 1.5 MeV--where the cross-section is small and steeply declining--to cause uncertainty about the error bars that should be quoted. Extensive studies with a cold oven showed that contaminants under these conditions were not troublesome. What these studies do not guard against is the possibility that contaminants arising within the oven only when the oven is white hot may occur. As the H to contaminant capture cross-section ratio is $\sim 10^{-3}$, a 100 ppm contaminant could cause errors $\sim$10%. At present, then, it appears that the MeV p on H results estimated a year ago continue to be valid over the range of measurement up to $\sim$ 1.5 MeV, with some expansion of error bars called for for projectile energies above this value. For the p on H measurements, submission for publication to Phys. Rev. A on completion of the analysis is again contemplated. Further collaborative experimentation in the two areas concerned in this sub-section is not planned for the subsequent contract year, as it appears heavy recent national laboratory fusion energy program investment in this area makes a duplication of effort inadvisable.

C.5. Zero Field Quantum Beats in Helium Projectiles Excited in Single Collisions in Thin Gas Targets

For several years the phenomenon of alignment in beam-foil collisions has been investigated in a number of laboratories, including the Research Institute for Physics in Stockholm. Here alignment refers to the unequal population of magnetic substates of an excited state formed in beam-foil excitation, leading to quantum beats in the light emitted downstream of the foil. Whether this phenomenon occurs in binary collisions in thin gas targets had not been investigated, perhaps due to the smearing out of the t = 0 definition provided by a thin foil target by the finite length of most gas target cells.

During a short visit of the author to the Research Institute in Stockholm on the way to GSI, his suggestion to try an exploratory thin gas cell experiment using the quantum beat measurement apparatus available there was readily accepted. The effort was successful, and resulted in publications A7, A24, and A33. We will now discuss a few features of this new technique.

A significant advantage of using foil excitation is the very short interaction time ($\sim 10^{-14}$ sec). A significant disadvantage is the inability to relate observed excited state alignment to simple binary collision amplitudes. Also breakage and thickening of the foil while exposed to the beam, limit the use of the technique with foils. To overcome these difficulties we have designed a short gas cell which can be moved along the beam, and is short enough to resolve a beat frequence of 1 GHz. As a first test of the technique, the J = 2 to 1, 659 MHz quantum beat signal in the decay of the He I transition 2s ^3S - 3p ^3P at 3889 Å was examined. Since the gas pressure in the cell is kept at the lowest possible level consistent with adequate signal strength, we are working in the single collision region, where a theoretical calculation of the degree of alignment in the excitation should be possible.

The 400 keV heavy ion accelerator of the Research Institute of Physics in Stockholm was used to accelerate $^4He^+$ ions to energies between 200 and 350 keV. The experimental arrangement was similar to that of a conventional quantum beat beam-foil experiment, with the exciter foil replaced by a 1 mm diameter beam stop and a 1.5 mm long gas cell held at a fixed distance from each other (Fig. 12). The target cell motion was accomplished by a stepping motor driving a precision screw. Argon was chosen for the exciter gas, since it is heavy enough to provide a large pressure difference at the cell walls, light enough to limit beam spread, and spherical enough to be of fundamental interest. The argon gas was fed

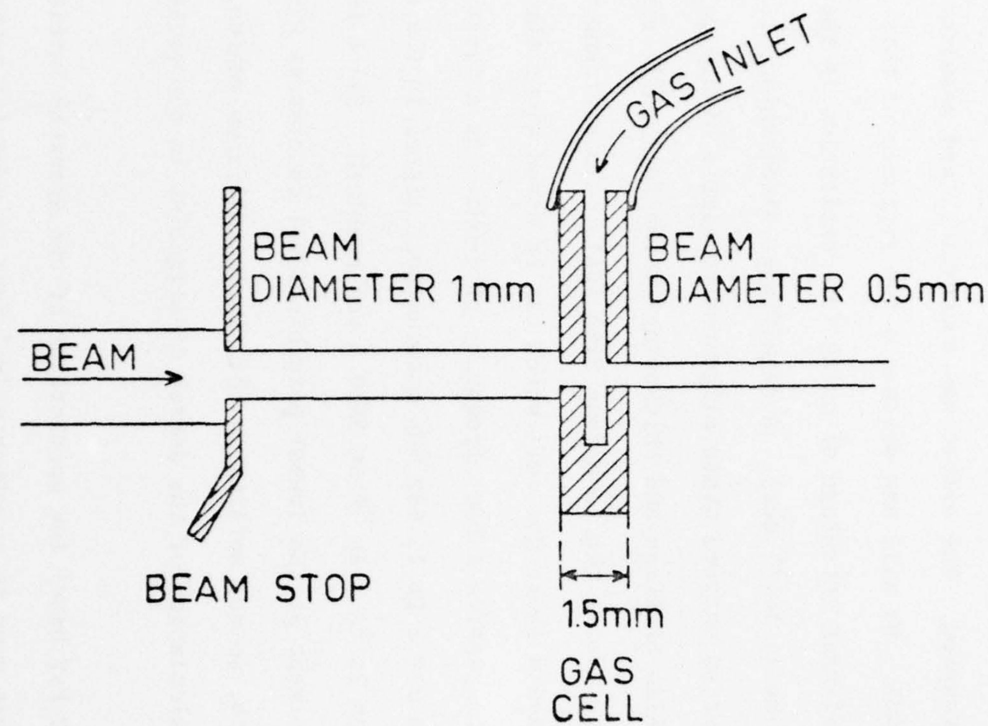

GAS INLET
BEAM
DIAMETER 1mm
BEAM
DIAMETER 0.5mm
BEAM
BEAM STOP
1.5mm
GAS
CELL

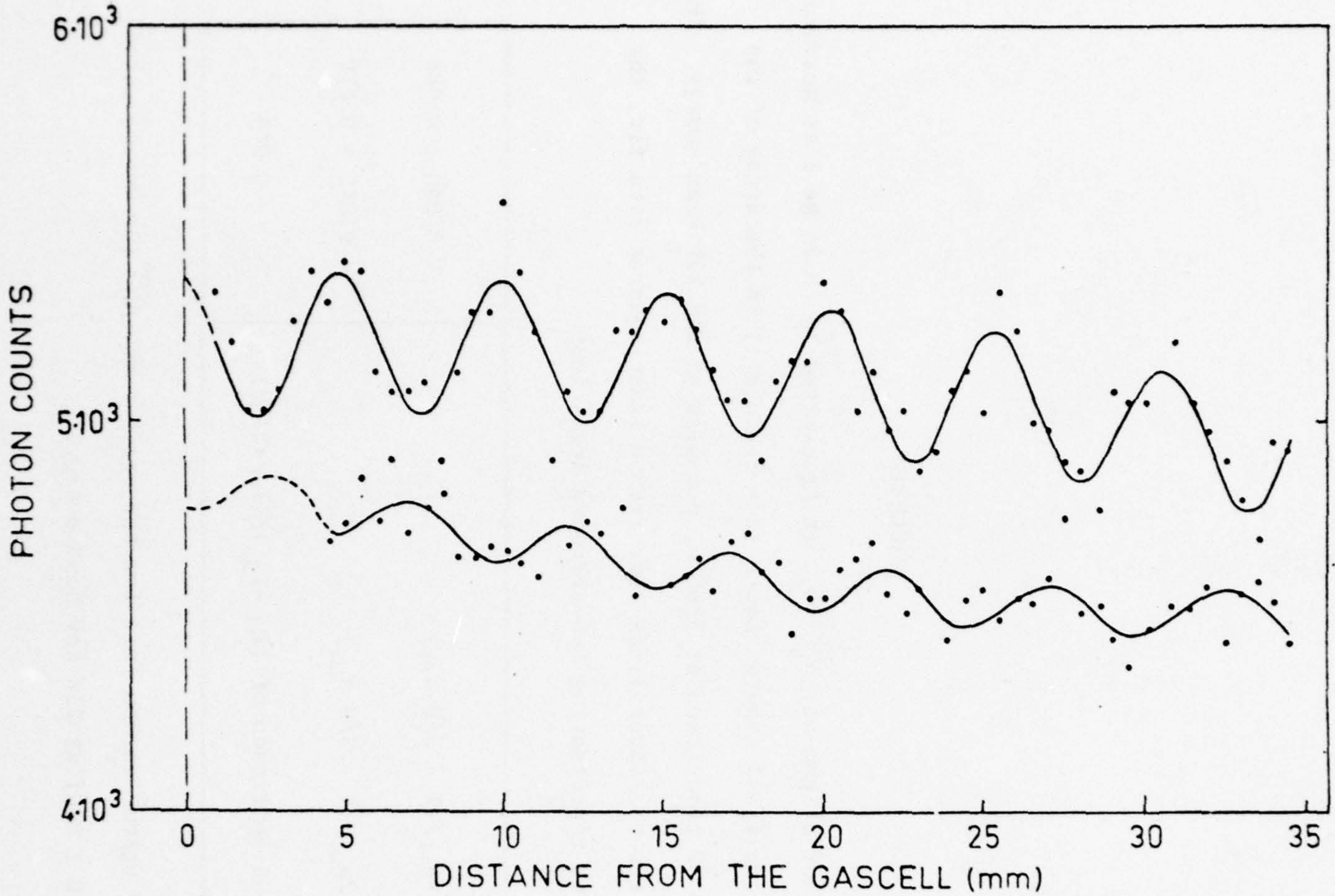
Fig. 12

into the gas cell through a flexible tube to facilitate the movement of the cell. Because of the cell length limitation, no differential pumping was used. The pressure difference between the cell and the target chamber was established only by the small beam entrance and exit apertures. To avoid excessive rest gas excitation outside the gas cell, the argon pressure was kept at such a low level that the pressure gradient outside the cell was only noticeable as a varying background within 1 mm from the cell. The total pressure in the target chamber was $\sim 1 \times 10^{-4}$ torr, which is still enough to produce a constant background of light from rest-gas excited beam particles. This background could be corrected for by measuring the rest-gas excitation between the 1 mm diameter beam collimator and the upstream cell wall. In a typical run at optimum pressure, this background correction amounted to 20% of the total signal. The 3889 Å line in He I was observed using a 35 cm Heath monochromator equipped with a cooled EMI 6256 photomultiplier. The coupling of the monochromator to the beam was achieved by two lenses giving a 1:1 correspondence between the 0.25 mm wide entrance slit and the length of the beam being observed. In the parallel light beam between the lenses, a Polawat 105 UV polarizer and a Hanle wedge depolarizer were located, thus making it possible to compare the intensity of light polarized parallel and perpendicular to the beam without correction for the instrumental polarization in the monochromator. Decay curves were generated by recording the light intensity as a function of cell position in 0.5 mm steps and adding together the result of several such runs. The scanning speed was regulated by a monitor photomultiplier, which recorded light at a fixed distance from the cell. The energy of the beam was measured to within 0.5% by a 0.5 m mean radius electrostatic analyzer.

In Fig. 13, a decay curve at 3889 Å is shown recorded in light polarized parallel ($I_{||}$) and perpendicular ($I_{\perp}$) to the beam. The light was observed at an angle of 90° to the beam. The beat frequency was measured to be 662 ± 9 MHz in good agreement with the more precise measurements by Tham who obtained the value 658.76 ± 0.13 MHz. As can be seen from the figure, the two polarization directions have a phase difference of π radians, with $I_{||}$ having a maximum at the gas cell position.

The adjacent table summarizes the measurements of $A_0^{col}(0)$ as obtained from this experiment, where A_0^{col} is $(\sigma_1-\sigma_0)/(\sigma_0+2\sigma_1)$. Here σ_0 and σ_1 refer to cross sections for population of m = 1 and 0 states, respectively. The results are compared with foil excitation data obtained by us under very similar conditions--the same beam energy (238 keV) and the same beam current after the exciter (2 μA). At 330 keV the beat signal indicated an alignment comparable to the one measured at 238 keV. A theoretical alignment calculation for this single-collision case is clearly desirable.

In this experiment we have demonstrated the possibility of using a moving gas-cell target in fast-beam quantum-beat experiments, when a moderate degree of spatial coherence is sufficient (beat frequencies of a few hundred MHz). The most appealing advantage of this new technique is the possibility of testing theoretical calculations of alignment of a few per cent or more for single binary collisions. Such small alignments are very difficult to determine in integral (non-quantum-beat) polarization measurements, because they tend to time average to nearly zero. The subtraction of comparable large numbers, $I_{||}$ and $I_{\perp}$, leads to great statistical errors, while imperfections in the polarizator may cause systematic errors. Similar limitations apply to integral-radiation, angular-distribution measurements. Reliable examination of the variation of alignment with beam energy (including the



$6 \cdot 10^3$
$5 \cdot 10^3$
$4 \cdot 10^3$
PHOTON COUNTS
0 5 10 15 20 25 30 35
DISTANCE FROM THE GASCELL (mm)

Fig. 13

TABLE IV

The degree of alignment, $A_0^{col}(0)$, in Ar excited 3p ^3P in He I as measured from the zero-field quantum beats (J = 2 - J = 1) in the decay of the 2s ^3S - 3p ^3P transition at 3889 Å, measured at 238 keV beam energy. The values in the two first lines come from a least-squares data fit, the error limits representing two standard deviations.

$A_0^{col}(0) = -a_{\parallel}/(1 - 5/9\ a_{\parallel})$	- 0.046 ± 0.008
$A_0^{col}(0) = 2a_{\perp}/(1 - 5/9\ a_{\perp})$	- 0.045 ± 0.019
$A_0^{col}(0)$ = -2 amplitude of $(I_{\parallel} - I_{\perp})/(I_{\parallel} + 2I_{\perp})$	- 0.044

Using a 10 μg/cm^2 carbon foil for the excitation, $A_0^{col}(0)$ was measured to be -0.080 ± 0.01 at 238 keV beam energy.

study of regions in which the alignment is small) under single-collision conditions, and eventual extension to study quenching of alignment under conditions of higher gas pressure are possible, fruitful applications of the new technique. It is hoped that collaborative measurements can continue as outlined in Section D of this proposal.

C.6. Discussion of Miscellaneous Publications, Activities, and Investigations Related to ONR-supported Research Activities and Publications

Several contributions to scientific books and magazines of a general nature are expected to be published during the forthcoming contract year. A1 is a book in the new Springer-Verlag Series, Topics in Modern Physics, edited by the author, and containing chapters by S. Brodsky and P. Mohr on quantum electrodynamics, by L. Armstrong on relativistic atomic structure theory, by J. S. Briggs on ion-atom collision theory, by P. Mokler and F. Folkmann on x-ray production by heavy ions, by N. Stolterfoht on electron production by heavy ions, by the author on extensions of beam foil spectroscopy, and by S. Datz on atomic collisions in solids. A2 is a didactic article for other physicists on the methods of BFS by D. J. Pegg, co-principal investigator. A4 is a more general article on this subject by the same author for the national readership of the magazine "Scientific American." A5 is a contribution concerning the work described in Section C.1 and D.1 of this proposal, solicited by S. J. Smith, outgoing chairman of the Division of Electron and Atomic Physics of the American Physical Society, for the annual review of highlights in physics published by the American Institute of Physics.

The work described in Section C.1.2 was accomplished in a collaboration with German scientists (Prof. K. O. Groeneveld, Dr. S. Schumann, Dr. R. Mann, Dr. P. Mokler, Prof. P. Armbruster, and others) at the GSI accelerator at Darmstadt, West Germany.

This new linac is the principal heavy particle accelerator in Germany, and has capabilities exceeding those of any analog in the U.S. at the present time. The collaboration began with a visit of Groeneveld to our laboratory during the period July-September, 1976, continued with a visit of Dr. R. Peterson to Groeneveld's laboratory in Germany during the period October, 1976 - January, 1977, continued with a stay of the author at GSI during the period April-September 1977, and amy continue with subsequent experiments both at GSI and at the Holifield Heavy Ion Accelerator under construction at Oak Ridge (see Section on Facilities). The author's residence in Germany was facilitated by receipt of an Alexander von Humboldt Foundation Senior U.S. Scientist Award. A senior Fulbright Hays grant for 1977-78 was also awarded the author, but could not be used for the same purpose because of regulations concerning dual grants. The research in sub-section C.5 was accomplished during a short stay of the author in Stockholm as a guest of the Research Institute for Physics, while en route to Germany.

Currently Dr. M. Suter from the laboratory of Dr. W. Wölfli at the Swiss Federal Institute of Technology at Zürich is in residence in our laboratory, and is a new participant in our ONR sponsored research, replacing R. S. Peterson, who has accepted a position at another University, and partially replacing R. S. Thoe, who has been appointed assistant professor at U.T.

Professor J. Wright (Univ. of New Hampshire) and H. Hayden (Univ. of Connecticut) have returned to their home institutions following sabbatical leave with our group. Their participation in ONR sponsored research was discussed in detail in our renewal proposal of one year ago.

D. Proposed Research for the Subsequent Contract Year

Some of the experiments to be proposed relate closely to accomplishments and discoveries of the past contract year. Others relate to more speculative, exploratory experiments. To the extent possible, our discussion will be parallel to the corresponding sub-sections of Section C, which deals with work accomplished in the present contract year.

D.1. Production of Multiple Electron Excitation and Ionization by Impact of Highly Charged Projectile Ions on Light Atoms and Molecules

As noted in Section C.1, when a highly charged projectile collides with a lighter atom, or a molecule containing lighter atoms, multiple electron vacancy production in both inner and outer shells of the target system is significantly more probable than single electron processes at impact parameters where the latter processes are likely. For example, it is found that for Ar^{18+} ions incident on Ne atoms at impact parameters intermediate between K and L shell radii, violent events like simultaneous removal of 9 of the 10 neon electrons accompanied by excitation of the 10th (e.g. to the hydrogenic 2p state) had substantial cross sections, even under single collision conditions. For high velocity collisions (beam energies of a few MeV/amu) the target atom recoil velocity is so small that interesting long term possibilities for precision experiments on ions in multiply ionized and excited states certainly exist. The large production cross sections and the reduction of Doppler spreads through reduction of v/c by some 3 to 4 orders of magnitude compared to fast, foil stripped beams undergoing decay in flight indicate good prospects for such experiments.

In the nearer term, however, fundamental questions concerning multiple electron excitation and ionization processes certainly exist. As also noted in Section C.1, it has never been clear what ultimately happens to the ejected electrons, either experimentally or theoretically. Do they end up in excited but bound states of the target particle or of the projectile? Or do they end up in continuum states, and if so, centered on which particle? Or if all of these events occur, what are the likelihoods of the various outcomes?

We propose to initiate a series of experiments on these questions which are likely to extend well beyond the forthcoming contract year. Approximate lower limits on cross sections for multiple bound state L-shell excitations are known from the $S^{\sim 12+}$, $Cl^{\sim 12+}$ on Ne experiments of the present contract year, as described in Section C.1.1. A present it is not known whether transitions into projectile or target-centered continuum states or into bound states of the projectile in the same collision have the greater probability.

The amount of theoretical guidance on such questions is minimal. In the model of Bottcher (J. Phys. B10, L445 (1977)), the highly charged projectile ions can escape with most of the system electrons, which become long term fellow travelers of the projectile as it moves outward from a collision, but are not attached to it in the sense of occupying bound orbits. Many-electron capture into continuum states of the projectile, a process whose importance for single electrons was realized a few years ago (Crooks and Rudd, Phys. Rev. Lett. 25, 1559 (1970), J. Macek, Phys. Rev. A1, 235 (1970)), is an appropriate description of what Bottcher asserts to be the dominant process. Eichler (Phys. Rev. A15, 1856 (1977)) has instead concentrated on a non-perturbative but otherwise more traditional description in terms of ionization of electrons into the target continuum within the framework of the so-called Magnus approximation. Since the assertion of Bottcher has not yet been tested experimentally, which mode of multiple ionization is in fact dominant is not yet established. However, our experiments on $S^{\sim 12+}$, $Cl^{\sim 12+}$ on Ne do show that multiple excitation of target electrons into higher, previously unoccupied bound orbits of the target atom is also extremely probable, indicating that multiple target electron excitation provides an important if not dominant contribution to the multiple electron rearrangement process, which may not be ignored compared to continuum capture processes.

D.1.1. Multiple Electron Excitation into Projectile Continuum States

We propose to begin experiments on multiple electron excitation into projectile centered continuum states for highly ionized projectiles traversing lighter gas targets. Construction has begun on apparatus incorporating a small spherical sector electrostatic analyzer whose entrant central ray coincides with the beam direction, and whose entrance focus lies near the center of a short target gas cell. The projectile beam passes through the large radius plate of the spherical sector analyzer for collection and normalization purposes. Target gas pressure is to be controlled and measured by a capacitance-manometer-based measurement and feedback control system. The apparatus will first be assembled, tested, and calibrated using the 50 keV accelerator system completed during the last contract year. When satisfactory agreement with the lower energy and charge state work at Nebraska, Georgia, and elsewhere is obtained, the apparatus will be moved to the ORNL tandem accelerator for use with high projectile charge state beams (e.g., $S^{\sim 12+}$ on Ne).

D.1.2. Projectile Charge State Dependence of the Production of the (1s2s2p) ^4P State of Lithiumlike Target Ions Under Single Collision Conditions

As noted in Section C.1.2, the (1s2s2p) ^4P state is the most intensely excited state in high charge state projectile excitation of lighter targets. Since the decay of this state arises from competition between Auger electron and M2 radiation emission whose rates are known, the fluorescence yield can be accurately estimated. Charge state dependence measurements will, therefore, overcome the ambiguity which affects many charge state dependence measurements in the x-ray channel. This ambiguity arises from poorly known, charge state dependent fluorescence yields. Such a charge state dependence measurement would test another, curious feature of Bottcher's model--significant structure in the charge state dependence of multiple electron excitation. In particular, Bottcher has calculated the charge state dependence of 10 electron excitation of neon by Ar^{q+} impact on neon at 1.4 MeV/amu. As his model also predicts that for smaller numbers of multiple L shell electron ejections the K-electron removal probability is the limiting probability in a product of many, it is plausible that such structure will occur in the 8 electron excitation needed to populate the 1s2s2p ^4P states. This experiment, suggested by the author while in residence at GSI, is presently continuing at that laboratory using the Auger electron spectroscopy facility there. At the moment a capacitance manometer monitored gas target is being prepared to replace the gas jet target whose density inhomogeneities have caused excessive data scatter in preliminary runs to date. It is anticipated that this experiment will continue on a partially collaborative basis during the coming contract year.

D.1.3. Delayed Coincidence Lifetime Measurements on Long-Lived Auger Emitting States of Multiply Ionized Target Atoms

Continuation of collaborative delayed coincidence lifetime measurements on Auger emitting states of C^{q+}, N^{q+}, O^{q+}, and Ne^{q+} ions at GSI as described in Section C.1.2 is proposed, assuming a continued close collaboration with our German colleagues turns out to be feasible. Efforts to make more systematic target gas pressure dependence measurements will begin when the gas cell apparatus referred to in sub-section D.1.2 is in place. Excited state quenching cross-section measurements are the objective here. Progress in the projects described in sub-sections D.1.2 and D.1.3 depend on the degree of success we experience in continuing this collaboration on a meaningful basis despite the separation of the GSI laboratory from locally available facilities.

D.1.4. Recoil Fragmentation Subsequent to High Projectile Charge State Impact on Molecules

To the extent that time permits we propose to continue the molecular fragment recoil studies which are the subject of papers A25 and A40. While these studies began collaboratively at GSI and will continue there on a partially collaborative basis, we propose to construct apparatus suitable for such studies locally as well. A new cylindrical mirror electrostatic analyzer is available for this purpose. As noted in Section C.1.2 and in the Section on Rationale and Facilities, the multiple rearrangement of the electrons of a heavily ionized target molecule between the atomic centers prior to separation is a type of dissociation phenomenon whose study is just beginning. Here again the small atomic recoil owing to the short interaction time a highly ionized projectile spends in the vicinity of a lighter target atom is a key feature of the excitation method, which is helpful in restoring an approximately two body aspect to the subsequent dissociation phenomenon. In particular, we propose to try analyzing the recoil ion energy and charge state spectra directly as opposed to indirectly (as at present) through analysis of the Auger electrons ejected from the fragments. A substantial effort to adapt a recently acquired cylindrical mirror analyzer to a new ultrahigh vacuum cross, associated flanging, valving, and supporting hardware will be required to accomplish this objective.

D.2. Collisional Production and Electron Spectroscopy of Core-Excited States of the Alkali Metals and Alkali-like Ions

As discussed in Section C.3, it is puzzling how steep the excitation function for population of such levels as Li $1s(2s2p)^3P\ ^2P$, $1s(2s2p)^1P\ ^2P$, and $1s2p^2\ ^2D$ for 10-50 keV energy Li^+ on He collisions seem to be, and how different the excitation functions for the singlet vs. triplet parentage ^2P transitions seem to be. A number of short discussions with J. S. Briggs, who has been visiting ORNL from Harwell recently, has led to a better understanding of the double rotational coupling mechanism which seems needed to account for strong population of the ^2D state. Further analysis of the data acquired during the past contract year, supplemented by such new data on this or other collision systems as seems required is proposed. Understanding how the 1s2s2p states are populated, perhaps through a subsequent transition starting from the ^2D state, is a basic goal. Accounting for the strong difference in excitation functions depending on whether one has singlet or triplet outer shell spin coupling is also a major goal. The reasons for this strong difference are not understood.

D.3. Completion of Lifetime and Quantum Beat Studies in Electrostatic Fine Structure ($\Delta n = 0$) Transitions in Few-Electron Metal Ions

What can be learned concerning fundamental atomic structure problems as well as related technical applications has been discussed extensively in Section C.2 of the present proposal and in our proposal of one year ago. We therefore restrict discussion here to describing how this work is to be continued, to what extent it is expected to be completed, and what new experimentation is contemplated.

A substantial amount of data on this subject has been acquired within the past contract year. Much of it has as yet only undergone analysis, and now requires preparation for publication in written form. Examples are $\Delta n = 0$ decay studies in Na-like Bromine (paper A27), Li-like and Be-like iron (A28), C-, N-, O-, and F-like chlorine (A29), Li-, Be-, and B-like chlorine (A30), Li-like aluminum and Be-like phosphorous (A31), and Li-like and Be-like silicon. Because of the large volume of such data, completion of preparation of such results for publication is expected to overlap into the subsequent contract year. Because of this large volume of new data and significant recent improvements in the agreement of theory and experiment, it is felt that further experiments in this area should generally be deferred in favor of new investigations in the subsequent contract year.

An exception is the unusual intensity beats discovered in M-shell $\Delta n = 0$ transitions, even those whose upper level corresponds to $J = 1/2$ (cf. article A15). While it was originally thought that hyperfine interactions might be involved, more recent observations of very similar beats in foil excited ^{58}Ni precludes this possibility. Hence new experiments designed to look for other effects which modulate cascade feed transitions are contemplated. A search for modulations in a longer wavelength feed transition in sodiumlike Cu or Ni seems a logical first step.

D.4. Alignment in Single Collisions by a Quantum Beat Technique

In Section C.5, the success of an attempt to measure the alignment tensor component A_0^{col} in the single collision process ($He^+ + Ar \rightarrow He\ 3\ {}^3P$) + ··· was described. While of course such alignment phenomena have been encountered for a number of years in foil excitation experiments, the key disadvantage of such foil excitation experiments is the complete absence of a detailed theory of what the anisotropy ought to be. Since the chance is much greater that reliable theoretical predictions can be made for binary ion-atom collisions at well defined velocity, and since then one has the possibility of comparing measured single collision alignments in foil and gas targets, it is proposed to continue such experiments by means of studying the beam energy dependence of such alignments comparatively as a function of beam energy, in the He^+-Ar and other collision systems. It is hoped that further collaboration with personnel of the Research Institute of Physics in Stockholm (J. Bromander, L. Liljeby, L. Lundin) on this subject will be possible. Ultimately it is hoped that it will be possible to understand the observed alignments in terms of molecular curve crossing models akin to those discussed in Sections C.3 and D.2.

RATIONALE OF THE PROPOSED RESEARCH

Accelerator based atomic and molecular physics continues to be a rapidly evolving new field. The present ability to create almost any ion charge and excitation state of any element at least as heavy as krypton and a good many charge and excitation states of substantially heavier elements has provided the technical means for studies of the structure and lifetimes of few-electron ions, photon and electron spectroscopy of both few- and many-electron excited states, and collisional production and quenching of these ions in both solid and gaseous targets. Many of the states found are multiply excited, have high angular momenta, high excitation energies, and decay not only by allowed processes but also through strong violation of the normal selection rules for radiative and autoionizing processes. Theories of electron excitation and ionization, electron rearrangement in ion-impact collisions, and the penetration of charged particles in matter are all receiving new experimental input from this research. New phenomena not previously considered by or quantitatively accounted for by these theories continue to crop up. Multiple ionization and excitation under single collision conditions are examples. Many of the observed phenomena are common to both ion beam experiments and to (often laser induced) plasma experiments. There are also siginificant differences among these excitation modes which require clarification. Characterization of even very basic phenomena - e.g., multiple ionization - is still rudimentary.

Subject matter under study in our laboratory includes fundamental atomic structure, inner and outer shell vacancy production by heavy particles, subsequent emission of radiation (light, x-rays, Auger electrons) during decay of atomic states of moving ions and of target atoms and molecules, the stripping and capture of electrons from moving ions into both bound and continuum states, the wavelengths and transition probabilities for excited heavy ions in high states of ionization (particularly heavy ions in plasmas), and collisional production of excited states of heavy ions that might be useful in xuv, uv, and x-ray laser development. These subfields within the larger field of accelerator based atomic and molecular physics are prominently mentioned in the recent National Academy of Sciences-National Research Council panel report (1976) surveying the larger field, an effort chaired by B. Crasemann. We believe the program outlined in this proposal contains many of the features strongly endorsed by this NAS-NRC panel.

Among our specific goals of the past few years have been studies of the excitation and decay modes of long-lived, often metastable states of highly ionized and excited ions, which decay mainly by photon and Auger electron emission through violation of selection rules. Since first order matrix elements describing transition probabilities are then zero, a measurement leverage advantage arises concerning more subtle, selection rule violating interactions like highly Z dependent magnetic or other relativistic interactions. Occasionally, consequences of quantum electrodynamic interactions also affect measured transition probabilities directly, resulting in opportunities for tests of qed.

With the advent of better relativistic transition probability calculations, improvement of configuration interaction treatments, and greater use of intermediate angular momentum coupling schemes where appropriate, the convergence of theory and experimental results in this area depicts great recent progress in both. It thus becomes logical to shift emphasis more in the direction of studying more poorly understood collision phenomena which govern population of these states of high excitation, ionization, and angular momentum, in both projectile and target systems. For highly ionized systems the interactions are strong, perturbation treatments of the electronic motion become less and less useful, and multiple electron transitions become the rule rather than the exception. A number of our current and proposed projects relate to the study of such phenomena.

Owing to the large cross-section for production of such multiply ionized and excited states in target atoms and molecules, it seems advantageous to concurrently explore the extent to which Doppler shifts and spreads which plague the spectroscopic accuracy of fast beam atomic structure experiments can be avoided. The outlook is brightest at as high collision velocities as possible, for then the recoil velocities are smallest.

In the field of chemistry, the multiple rearrangement of the electrons of a target molecule between the atomic centers is a type of dissociation phenomenon whose study is just beginning. Here again, it is technically natural to study such phenomena concurrently, using excitation by fast, highly ionized projectiles to suddenly produce multiply ionized, initial molecular states in, for example, a diatomic molecule. Again, the advantage at high collision velocities is the rapid removal of the exciting particle to large distances and the small atomic recoil, permitting study of an approximately two-body break up process in which multiple electron transitions are important.

Each of these four program areas is represented in sections C and D of the present proposal, which deal respectively with current and proposed research projects. In the subsequent section, the facilities available to us for carrying out our program in each of these areas are described.

FACILITIES

The abstract and summary work statement of this proposal together with the section concerning rationale serve as an adequate introduction to the type of experimental problems we have been interested in in the past and the directions in which our experimental program has been moving. We discuss here the overall experimental basis of our program and the facilities available for it. We rely heavily on accelerator time and basic accelerator support facilities provided to us mainly by the Oak Ridge National Laboratory and on occasion by the Brookhaven National Laboratory, the Lawrence Berkeley Laboratory, the Gesellschaft für Schwerionenforschung, or other installations. It has been DOE and FRG policy to make time on these accelerators available to qualified outside users whose experimental proposals are favorably reviewed by scheduling committees at the installation concerned. Generally, these facilities are available at no charge to the user, who however, must provide all experimental equipment and personnel specific to a particular experiment proposed by the user. In recent months our users' group has been allocated more than 80% of the time it has requested on the Oak Ridge tandem acclerator, on the Oak Ridge Isochronous Cyclotron, on the Oak Ridge multiply charged ion source test facility, on the Brookhaven MP tandem accelerator, on the Berkeley HILAC, and on the GSI UNILAC for the particular experiments we have proposed. While there is no guarantee that we will continue to be allocated accelerator time at the same rate, we have every expectation that such time will be made available, either at ORNL or at other national and international facilities which customarily serve outside users. Hence, the budget for this proposal does not reflect total costs of the work proposed, but only the fraction of the cost which is concerned with salaries of scientific personnel and with operating, capital equipment, and travel expenditures specific to the proposed work. Budgeted costs reflect, then, only approximately half of the total cost of the proposed work!

Several accelerators at the Oak Ridge National Laboratory are equipped for the acceleration of heavy ions suitable for atomic physics and are regularly used by us. In this subsection the kinds of ions, their charge states, and energies available at each accelerator are described.

The ORNL Tandem Van de Graaff Accelerator - This machine is a type EN tandem built by High Voltage Engineering Corporation. The useful upper voltage limit is 6.5 MV and the machine has been run as low as 1.5 MV without difficulty. Its ion sources are capable of producing beams of most heavy ions up to energies of 40 to 50 MeV, in quantities ranging from nanoamperes to microamperes depending upon the ion and the charge state required. The machine has been put to effective use with beams of H, D, ^{3}He, ^{4}He, ^{12}C, ^{13}C, ^{14}N, ^{16}O, ^{18}O, ^{19}F, ^{27}Al, ^{28}Si, ^{32}S, ^{35}Cl, ^{37}Cl, ^{56}Fe, ^{58}Ni, ^{63}Cu, ^{79}Br, ^{81}Br, ^{127}I, ^{198}Au, and ^{238}U. A universal ion source of the Middleton type provides these and many other beams. For light ions nanosecond pulsed beams are available. A broad array of nuclear and atomic instruments is available, including a broad range magnetic spectrometer, scattering chambers for both solid and gaseous targets, electrostatic analyzers for ion charge state analysis and for electron spectra observation, ultraviolet and x-ray dispersion instruments and Ge(Li) and Si(Li) detectors. Electronic equipment and computing facilities are available for data acquisition and analysis. A new two stage buncher, to be used eventually on the 25 MV accelerator under construction, is now in place at the EN.

The ORNL 5.5 MV Van de Graaff Accelerator - This machine is fitted with a hot cathode Nielsen type ion source with provision for acceleration of ions of almost any element in the periodic table. Target facilities are now in place for observation of atomic x-ray phenomena. A target facility has been built to explore radiation damage effects. Computer facilities of the Tandem Accelerator are accessible through cable links in the control room of this machine and also at the control room of the 3 MV Van de Graaff accelerator.

The Oak Ridge Isochronous Cyclotron (ORIC) - This accelerator is equipped to accelerate many different ion species and a partial list of the ions which have been accelerated is shown in the following Table. A wide range of instruments is available, as is the case with the Tandem Accelerator. A broad range magnetic spectrograph is included in the list of instruments, as well as a large number of scattering chambers, detectors, and target systems. A wide variety of other atomic collisions programs in addition to our own are pursued at both the Tandem Accelerator and at ORIC. ORIC is expected to be part of the new Holifield Heavy Ion Laboratory being constructed at ORNL, as described in a subsequent section of this chapter.

ORIC EXTRACTED HEAVY ION BEAMS

Particle	Harmonic	Maximum ORIC Energy[a] (MeV)	External Beam Current eμA[b]	Source Feed
$^{6}Li^{1+}$	3	15	1[c]	LiF + Ne
$^{6}Li^{2+}$	1	60	8[c]	LiF + Ne
$^{6}Li^{3+}$	1	135	40 enA[c]	LiF + Ne
$^{7}Li^{1+}$	1	12.9	650 enA	LiF + Ne
$^{7}Li^{2+}$	1	51	8	LiF + Ne
$^{10}B^{2+}$	3	36	15 enA	BF_3
$^{10}B^{3+}$	3	81	8	BF_3
$^{10}B^{4+}$	1	144	>10 enA	BF_3
$^{11}B^{3+}$	1	73.6	30	BF_3
$^{12}C^{1+}$	5	7.5	12 enA	CO
$^{12}C^{2+}$	3	30	1 enA	CO
$^{12}C^{3+}$	3	67	>10	CO
$^{12}C^{4+}$	1	120	>12	CO
$^{12}C^{5+}$	1	187	40 enA	CO
$^{12}C^{6+}$	1	270	∿1 epA	CO
$^{13}C^{4+}$	1	110	15	CO_2
$^{14}N^{2+}$	3	26	>20	N_2
$^{14}N^{4+}$	1	103	>20	N_2
$^{14}N^{5+}$	1	161	2	N_2
$^{15}N^{3+}$	3	36	1 enA	N_2
$^{15}N^{4+}$	3	96	8[c]	N_2
$^{16}O^{1+}$	5	5	1.3	O_2
$^{16}O^{2+}$	3	22.5	5	O_2
$^{16}O^{3+}$	3	50	300 enA	O_2
$^{16}O^{4+}$	3	90	>4	O_2
$^{16}O^{5+}$	1	140	20	O_2
$^{16}O^{6+}$	1	202	1.1	O_2
$^{17}O^{1+}$	5	4.7	2.2 enA	O_2
$^{18}O^{2+}$	3	20	10 enA	O_2
$^{18}O^{5+}$	1	125	20[c]	O_2
$^{19}F^{2+}$	5	18.9	1.5	BF_3
$^{19}F^{6+}$	1	170	1	BF_3
$^{20}Ne^{1+}$	7	4.5	19[e]	Ne
$^{20}Ne^{3+}$	5	36.6	5	Ne
$^{20}Ne^{4+}$	3	72	>1	Ne
$^{20}Ne^{5+}$	3	112	>1	Ne
$^{20}Ne^{6+}$	1	162	3	Ne
$^{20}Ne^{7+}$	1	220	27 enA	Ne + Xe
$^{21}Ne^{1+}$	7	4.3	0.7 enA	Ne
$^{22}Ne^{2+}$	3	16	800 enA	Ne
$^{22}Ne^{4+}$	3	65.5	600 enA	Ne
$^{22}Ne^{5+}$	3	102	300 enA	Ne

ORIC EXTRACTED HEAVY ION BEAMS

Particle	Harmonic	Maximum ORIC Energy[a] (MeV)	External Beam Current eμA[b]	Source Feed
$^{24}Mg^{5+}$	3	93.8	47 enA	MgF_2 + Xe
$^{24}Mg^{6+}$	3	135	0.3 enA	MgF_2 + Xe
$^{27}Al^{4+}$			100 enA	Al + Xe
$^{27}Al^{5+}$			12 enA	Al + Xe
$^{28}Si^{3+}$	3	29	0.1 enA[d]	
$^{28}Si^{5+}$	3	80.4	0.93	Si + Xe
$^{28}Si^{6+}$	3	115.7	10 enA	Si + Xe
$^{29}Si^{3+}$	5	27.9	100 part/sec[d]	Ne
$^{30}Si^{6+}$	3	108	1 epA	SiF_4
$^{32}S^{4+}$	3	22.5	9 enA[d]	
$^{32}S^{6+}$	3	101	100 enA	H_2S
$^{34}S^{2+}$	5	9.4	300 enA	H_2S
$^{35}Cl^{3+}$	7	23	10 enA	Cl_2
$^{35}Cl^{5+}$	3	64	>1 enA	Cl_2
$^{35}Cl^{7+}$	3	126	900 enA	Cl_2
$^{36}Ar^{9+}$	3	202	$\sim 5 \times 10^5$ part/sec	Ar
$^{40}Ar^{2+}$	7	9	300 enA[e]	Ar
$^{40}Ar^{3+}$	5	20.2	3[e]	Ar
$^{40}Ar^{4+}$	3	36	34	Ar
$^{40}Ar^{5+}$	3	56	1	Ar
$^{40}Ar^{6+}$	3	81	6	Ar
$^{40}Ar^{7+}$	3	110	1.6	Ar
$^{40}Ar^{8+}$	3	144	1.2	Ar
$^{40}Ar^{9+}$	3	182	15 enA	Ar
$^{40}Ar^{10+}$	3	225	$\sim 5 \times 10^4$ part/sec	Ar
$^{40}Ar^{11+}$	1	272	250 part/sec	Ar
$^{40}Ca^{6+}$	3	81	300 enA	Ca + Xe
$^{40}Ca^{7+}$	3	110	700 enA	Ca + Kr
$^{40}Ca^{8+}$	3	144	12 enA	Ca + Kr
$^{48}Ti^{5+}$	3	46.9	1.2	Ti + Xe
$^{48}Ti^{6+}$	3	70.4	360 enA	Ti + Xe
$^{48}Ti^{7+}$	3	91.9	100 enA	Ti + Xe
$^{48}Ti^{9+}$	3	150	0.3 enA	Ti + Xe
$^{52}Cr^{2+}$	9	6.9	1 enA[d]	
$^{55}Mn^{5+}$	3	40.9	30 enA[d]	Xe
$^{54}Fe^{7+}$	3	81.7	21 enA	Fe + Xe
$^{54}Fe^{8+}$	3	106.7	9 enA	Fe + Xe
$^{56}Fe^{5+}$	3	40.2	1.2	Fe + Xe
$^{56}Fe^{6+}$	3	58	400 enA	Fe + Xe
$^{56}Fe^{7+}$	3	75	10 enA	Fe + Xe

ORIC EXTRACTED HEAVY ION BEAMS

Particle	Harmonic	Maximum ORIC Energy[a] (MeV)	External Beam Current eμA[b]	Source Feed
$^{56}Fe^{8+}$	3	103	5 enA	Fe + Xe
$^{56}Fe^{9+}$	3	130	4 enA	Fe + Xe
$^{56}Fe^{10+}$	3	160	0.02 enA	Fe + Ne
$^{56}Fe^{11+}$	3	194	500 part/sec	Fe + Ne
$^{58}Ni^{5+}$	3	38.8	1.5	Ni + Xe
$^{58}Ni^{6+}$	3	55.8	3.5	Ni + Xe
$^{58}Ni^{7+}$	3	76	3	Ni + Xe
$^{58}Ni^{8+}$	3	99.3	30 enA	Ni + Xe
$^{63}Cu^{3+}$	7	12.9	15 enA	$Cu + Cl_2$
$^{63}Cu^{6+}$	3	51.4	1.2	Cu + Xe
$^{63}Cu^{7+}$	3	70	275 enA	Cu + Xe
$^{63}Cu^{9+}$	3	116	1 enA[d]	
$^{65}Cu^{6+}$	3	49.8	450 enA	Cu + Xe
$^{64}Zn^{6+}$	3	50.6	1.5	Zn + Xe
$^{64}Zn^{7+}$	3	68.9	100 enA	Zn + Xe
$^{66}Zn^{6+}$	3	49	0.1 enA[d]	
$^{78}Kr^{3+}$	9	10.4	10 enA	Kr
$^{83}Kr^{9+}$	3	87.8	2 enA	Kr
$^{84}Kr^{3+}$	9	9.6	32 enA	Kr
$^{84}Kr^{4+}$	7	17.1	1	Kr
$^{84}Kr^{5+}$	5	26.8	2.2	Kr
$^{84}Kr^{6+}$	5	38.6	150 enA[e]	Kr
$^{84}Kr^{9+}$	3	87	20 enA	Kr
$^{86}Kr^{6+}$	5	37.7	< 1 enA[e]	Kr
$^{93}Nb^{5+}$	5	24.2	70 enA	Nb + Xe
$^{93}Nb^{6+}$	5	34.8	70 enA	Nb + Xe
$^{93}Nb^{7+}$	5	47.4	35 enA	Nb + Xe
$^{93}Nb^{8+}$	5	61.9	1.8 enA	Nb + Xe
$^{93}Nb^{9+}$	5	78.4	2×10^5 part/sec	Nb + Xe
$^{128}Xe^{7+}$	5	34.5	1 enA	Xe
$^{129}Xe^{5+}$	7	17.4	3 enA[e]	Xe
$^{129}Xe^{7+}$	5	34.2	90 enA[e]	Xe
$^{129}Xe^{8+}$	5	44.7	13 enA[e]	Xe
$^{129}Xe^{9+}$	5	56.5	0.4 enA[e]	Xe
$^{129}Xe^{12+}$	3	100.5	1.3 enA	Xe
$^{130}Xe^{7+}$	5	33.9	4.5 enA	Xe
$^{131}Xe^{7+}$	5	33.7	15 enA	Xe
$^{132}Xe^{7+}$	5	33.4	20 enA	Xe
$^{132}Xe^{12+}$	3	98	0.1 enA	Xe
$^{134}Xe^{7+}$	5	32.9	8 enA	Xe

ORIC EXTRACTED HEAVY ION BEAMS

Particle	Harmonic	Maximum ORIC Energy[a] (MeV)	External Beam Current eμA[b]	Source Feed
$^{181}Ta^{6}$	9	17.9	1 enA	$Ta + Cl_2$
$^{181}Ta^{8}$	7	31.8	0.2 epA	$Ta + Cl_2$
$^{181}Ta^{9}$	7	40.3	0.5 epA	$Ta + Cl_2$

[a]Based on 90 q^2/A

[b]Electrical microamperes except as noted

[c]Enriched isotopic abundance source feed

[d]From ion source material of construction

[e]Ion source with dc extraction

ORIC Multiply Charged Ion Source Facility - This facility was originally constructed as part of a program to investigate and develop advanced ion-source systems for the production of multiply-charged ions to be used in the accelerators at ORNL. The facility is equipped to accelerate multiply charged ions to energies of 4 to 300 keV, depending upon ion charge. The beams are magnetically analyzed and they are usable for x-ray and other atomic collision experiments which are designed for observation of low energy ions of multiple charge. Characteristics of the beams now available from this facility are given by the following performance parameters. Energies $E = (4 \text{ to } 36) \times q$ keV, where q = ion charge, at a resolution $\Delta E/E$ = better than 1/2%. The beams are characterized by an emittance area of 200 - 300 mm-mr at 30 keV, a minimum quadrupole focal length of 38 cm, a maximum divergence (full angle) of 83.5 mr, and a minimum spot size of 3.6 mm. All of the beams extracted from ORIC are produced by an identical source. Because of charge exchange losses, the ORIC beam intensities are lower limits to the highly charged ion source facility beam intensities.

At the present time, the principal use of the multiply charged source is atomic collisions research. The in house portion of such research is devoted exclusively to atomic collisions problems related to the production of controlled thermonuclear fusion. External use of the facility by university users' groups has occupied about 30% of the available time on the facility, and has involved our own UTK accelerator based atomic physics group and also the Yale atomic physics group, working jointly with us on projects of mutual interest. The Ne^{q+} on Ne collision experiments, and the electron capture experiments with B^{q+}, C^{q+},

N^{q+}, O^{q+}, and F^{q+} beams on atomic H and various permanent gases discussed in Section C of our proposal of one year ago are examples of our use of the facility.

<u>The University Isotope Separator at Oak Ridge</u> - In addition to the above facilities, occasional use is made of a machine owned and operated by a consortium of fourteen universities known as UNISOR. The dedicated use of this machine is the study of short-lived isotopes created by ORIC on-line bombardment of gas targets located in the UNISOR ion source. When ORIC is otherwise engaged, however, a universal ion source similar to the one described above can be installed. We have thus far used microampere beams of $\sim$ 30-70 keV Li^+, Na^+, Mg^+, and K^+ beams in conjunction with the studies of core-excited states in the alkalis mentioned earlier in this and previous proposals.

<u>The Brookhaven MP Tandem Van de Graaff Facility</u> - The available equipment at this facility is highly similar to that already described under the heading ORNL Tandem Van de Graaff Facility, including the availability of a nearly identical list of metal ion beams produced by a unis source of the same type as exists at ORNL. The principal advantage of this facility is the availability of terminal voltages in the 10-12 MV range, extending the energy range (and thereby charge state range) of the various beams to $\gtrsim$ 100 MeV. A drawback is the lack of availability of machine time in amounts useful for long runs with highly dispersive spectroscopic instruments. Hence, short term experiments with high data acquisition rates requiring the highest ion energies of interest to us are carried out at the MP facility, whereas longer runs involving high dispersion experiments on lower energy beams are carried out at the ORNL Tandem. An example of recent work with the higher energy

Brookhaven MP Tandem Facility

August 1977

Two Stage Beams

Ion	Ion Energy (MeV)	Negative I-injected (μA)	Analyzed Beam Current (nA)	Charge State	Ion Source
^{1}H	20	5.000	3000.0	1	H
	27	2.300	600.0	1	U
^{4}He	34	1.000	60.0	2	G
	32	0.230	110.0	2	G
^{6}Li	42	0.600	600.0	3	U
	36	0.570	450.0	3	G
^{7}Li	56	0.120	165.0	3	U
	36	1.100	1000.0	3	G
^{9}Be	70	0.050	18.0	5	U
	39	0.600	80.0	4	U
^{10}B	70	0.050	4.5	5	U
^{11}B	40	0.600	85.0	4	U
	35	2.000	30.0	4	U
	50	0.900	500.0	4	U
^{12}C	28	2.000	1300.0	4	U
	83	1.300	240.0	6	U
^{13}C	50	0.700	200.0	5	U
	68	2.000	500.0	6	U
^{14}N	42	0.120	100.0	5	U
	68	2.100	400.0	5	H
	85	1.800	10.0	7	H
^{15}N	55	0.900	400.0	5	H
	70	2.000	250.0	6	H

Two Stage Beams

Ion	Ion Energy (MeV)	Negative I-injected (μA)	Analyzed Beam Current (nA)	Charge State	Ion Source
^{16}O	52	2.100	2200.0	5	H
	110	2.500	500.0	7-8	U
^{13}O	65	0.500	800.0	6	U
	110	2.000	175.0	8	U
^{19}F	65	1.300	500.0	6	U
^{24}Mg	30	0.300	25.0	5	U
^{27}Al	25	0.300	100.0	3	U
	50	0.600	90.0	5	U
^{28}Si	87	1.000	1800.0	8	U
	121	0.300	20.0	10	U
^{31}P	130	1.500	80.0	9-12	U
	90	0.600	400.0	8	U
^{32}S	110	1.000	800.0	9	U
	160	2.200	250.0	13	U
^{35}Cl	200	0.300	2.5	12-14	U
	79	2.700	580.0	8	U
	140	2.800	35.0	11	U
^{40}Ca	130	0.020	5.0	10	U
	118	0.250	8.0	10	U
^{45}Sc	98	0.030	3.0	8	U
^{48}Ti	79	0.200	60.0	6	U
^{51}V	92	0.060	5.0	8	U
^{56}Fe	30	0.400	150.0	4	U
	98	0.480	70.0	9	U
	110	1.800	60.0	6-12	U
	130	0.070	30.0	10	U

Two Stage Beams

Ion	Ion Energy (MeV)	Negative I-injected (μA)	Analyzed Beam Current (nA)	Charge State	Ion Source
^{58}Ni	97	0.690	90.0	10	U
	197	0.500	10.0	10-16	U
^{63}Cu	80	0.400	700.0	6	U
	120	0.800	150.0	10	U
^{64}Zn	103	0.200	15.0	9	U
^{74}Ge	42	2.000	500.0	5	U
	180	0.250	13.0	10-16	U
^{79}Br	151	0.700	30.0	14	U
	125	0.200	10.0	10	U
^{81}Br	132	1.700	7.0	13	U
	125	0.200	10.0	10	U
^{88}Sr	114	0.020	3.0	10	U
	84	0.650	200.0	8	U
^{93}Nb	42	0.200	180.0	6	U
^{98}Mo	134	1.000	15.0	10	U
	123	0.600	60.0	10	U
^{127}I	100	1.500	300.0	10	U
	90	2.500	300.0	9	U
^{132}Xe	89	0.020	1.0	9	U
	93	0.010	0.5	9	U
^{184}W		0.600			
^{197}Au	156	2.000	15.0	12	U
	99	1.300	40.0	10	U
^{208}Pb	110	0.550	12.0	10	U
^{238}U	113	0.020	0.8	11	U
	130	0.026	0.33	12	U

Three Stage Beams

Ion	Ion Energy (MeV)	Negative I-injected (μA)	Analyzed Beam Current (nA)	Charge State	Ion Source
^{1}H	31	3.000	1500.0	1	U
^{2}H	33	0.600	500.0	1	U
^{7}Li	60	0.270	360.0	3	U
^{9}Be	59	0.200	3.0	4	U
^{12}C	100	0.300	120.0	6	U
	90	0.550	600.0	6	U
^{13}C	72	0.010	5.0	6	U
^{16}O	125	2.000	1000.0	7-8	U
	100	1.500	250.0	8	U
^{18}O	120	0.500	200.0	7-8	U
	102	2.000	150.0	7	U
	63	0.650	450.0	6	U
^{32}S	151	1.300	900.0	9-12	U
	200	2.200	8.0	11-15	U
^{35}Cl	200	1.900	250.0	10-14	U
	120	0.700	400.0	10	U
^{37}Cl	200	2.200	150.0	10-14	U
^{56}Fe	260	0.350	4.0	13-19	U
^{58}Ni	230	0.230	15.0	11-18	U
^{65}Cu	268	0.060	6.0	13-20	U
^{79}Br	226	0.120	12.0	13-18	U
^{127}I	290	0.300	30.0	14-24	U
	318	0.230	1.2	14-27	U

U - Middleton type sputter ion source.

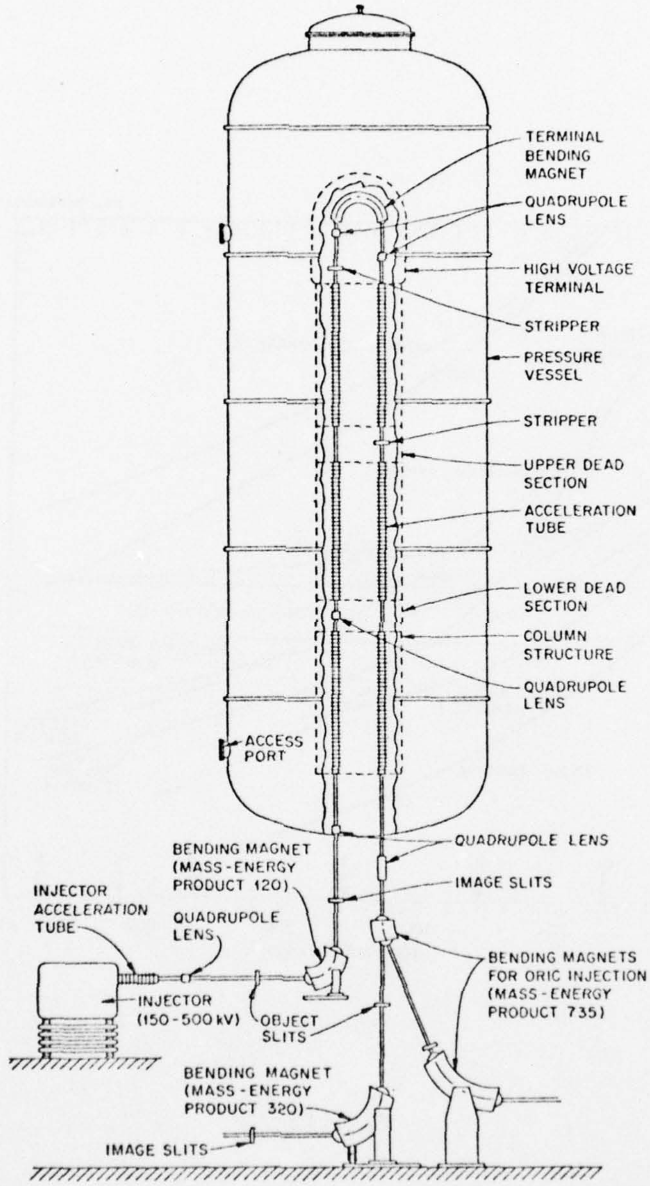
H - Direct extraction duoplasmatron.

G - Lithium vapor exchange source.

beams is the experiment on intensity beats in the resonance transition in sodiumlike copper discussed in Section C of this proposal. A list of available beams, intensities, charge states, and energies is provided in the accompanying table.

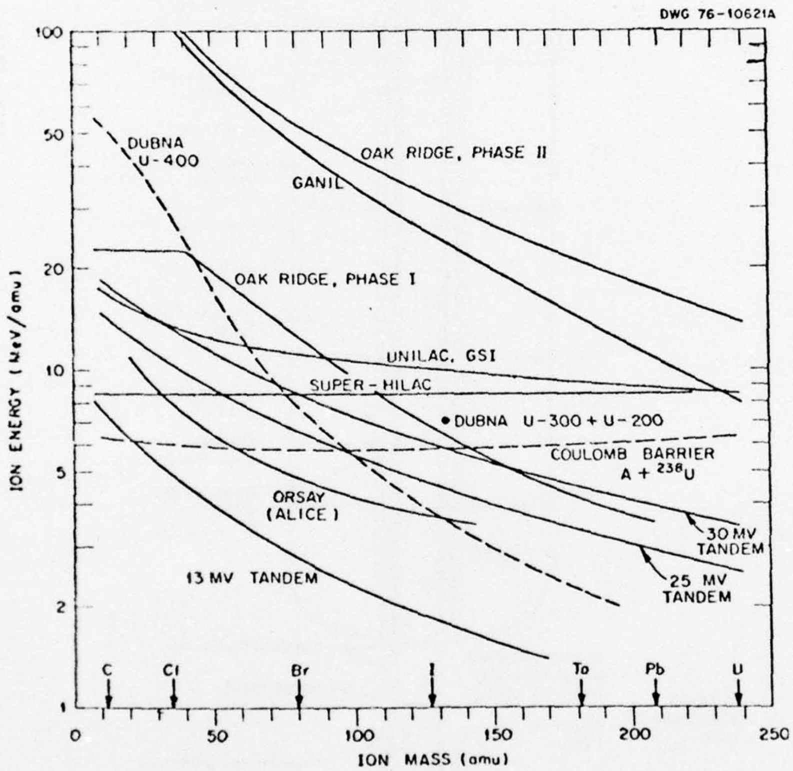
The Unilac Heavy Ion Accelerator Facility at Darmstadt, West Germany - As discussed in Sections C and D, collaborative work with personnel of the IFK of the University of Frankfurt and personnel of the Unilac accelerator facility began with experiments at the ORNL Tandem Van de Graaff a year ago, continued at the Unilac facility during April - September, 1977, and will continue in the forthcoming year. The Unilac accelerator is an rf linac device and has a nearly flat energy per nucleon beam characteristic, permitting use of beams $\sim$ 8 MeV/nucleon energy over the entire periodic table. Parallel use of a 1.4 MeV/nucleon beam, which is exclusively of interest for atomic physics, can occur simultaneously with the use of the full energy beam for nuclear experiments. For example, 1.4 MeV/nucleon beams of Ar^{12+}, Kr^{26+}, and Xe^{31+} ions are now available at target intensities $\sim$ 400 nA, 80 nA, and 20 nA. In the next year we plan to use these beams to continue the charge state dependence, lifetime, and Auger line shape experiments discussed in Section D. This collaboration is expected to continue with eventual use of the Holifield Heavy Ion Accelerator facility, presently being constructed at ORNL and scheduled for beam delivery in early 1979, for further atomic structure and collisions experiments.

Holifield Heavy Ion Accelerator Laboratory - This new facility just referred to in the previous subsection involves construction of the 25 MV tandem accelerator--the nation's largest--sketched in Fig. 14, which will then inject into ORIC for higher energy operation. A useful diagram of attainable and proposed energies and beam intensities in the Holifield, HILAC, and Bevalac accelerators (the latter two are at Berkeley) is shown in Fig. 15. As can be seen ORNL will have the prime national facilities for beams of useful ($\sim$ microampere) intensities throughout the energy range appropriate to the study of atomic (as distinct from nuclear) collision phenomena. Hence, from a facilities standpoint, the future of our particular program of atomic collisions research is an especially bright one.



A diagram of the layout of the 25-MV tandem now under construction at Oak Ridge.

Fig. 14



DWG 76-10621A
100
50
20
10
5
2
1
ION ENERGY (MeV/amu)
DUBNA U-400
OAK RIDGE, PHASE II
GANIL
OAK RIDGE, PHASE I
UNILAC, GSI
SUPER-HILAC
DUBNA U-300 + U-200
COULOMB BARRIER A + ^{238}U
ORSAY (ALICE)
30 MV TANDEM
25 MV TANDEM
13 MV TANDEM
C
Cl
Br
I
Ta
Pb
U
0
50
100
150
200
250
ION MASS (amu)

Fig. 15

LIST OF PERSONNEL WHO HAVE COLLABORATED IN ONR SUPPORTED RESEARCH

A. Personnel who have regularly participated in ONR sponsored research

Name	Title
S. B. Elston	Postdoctoral Research Associate
J. P. Forester	Graduate Research Assistant
P. M. Griffin	Physicist, Oak Ridge National Laboratory
K. O. Groeneveld	Visiting Professor
H. H. Haselton	Postdoctoral Research Associate
H. Hayden	Visiting Associate Professor
R. Laubert	Visiting Professor
K. H. Liao	Postdoctoral Research Associate
J. R. Mowat	Visiting Assistant Professor
D. J. Pegg	Associate Professor and Co-principal Investigator
R. S. Peterson	Graduate Research Assistant
I. A. Sellin	Principal Investigator
S. Schumann	Postdoctoral Research Associate
R. S. Thoe	Assistant Professor
C. R. Vane	Graduate Research Assistant
J. Wright	Visiting Associate Professor

B. Other Occasional Collaborators who have participated in ONR Supported Work

Name	Title
B. R. Appleton	Physicist, Oak Ridge National Laboratory
S. Bashkin	Professor, University of Arizona
James Bayfield	Professor, University of Pittsburgh

Name	Title
M. D. Brown	Physicist, Naval Surface Weapons Center
J. Cecci	Physicist, Princeton Plasma Physics Laboratory
D. Grandall	Physicist, Oak Ridge National Laboratory
S. Datz	Associate Director, Chemistry Division, Oak Ridge National Laboratory
D. Dietrich	Postdoctoral Research Associate, Univ. of Arizona
B. L. Donnally	Chairman, Physics Department, Lake Forest College
H. J. Frischkorn	Graduate Research Assistant, Univ. of Frankfurt/M
L. Gardiner	Postdoctoral Research Associate, Univ. of Pittsburgh
H. Gould	Physicist, Lawrence Berkeley Laboratory
B. Johnson	Physicist, Oak Ridge National Laboratory
K. Jones	Physicist, Brookhaven National Laboratory
R. Kauffman	Postdoctoral Research Associate, Kansas St. Univ.
H. Kim	Physicist, Oak Ridge National Laboratory
T. Kruse	Professor, Rutgers University
P. Koch	Assistant Professor, Yale University
J. Leavitt	Professor, University of Arizona
R. Mann	Postdoctoral Research Associate, Univ. of Frankfurt/M
J. R. Macdonald	Professor, Kansas State University
R. Marrus	Professor, University of California at Berkeley
D. Pisano	Physicist, Brookhaven National Laboratory
P. Richard	Professor, Kansas State University
D. Rosich	Graduate Research Assistant, Univ. of Frankfurt/M
R. L. Smick	Postdoctoral Research Associate, Univ. of Tennessee
W. W. Smith	Professor, University of Connecticut
R. R. Turtle	Postdoctoral Research Associate, Univ. of Tennessee

VITA OF PRINCIPAL INVESTIGATOR

VITA

Ivan A. Sellin

Present Position - Professor of Physics, University of Tennessee and Principal Investigator, UT/ORNL Accelerator Atomic Physics Group, Oak Ridge National Laboratory, 1974 to present.

Previous Positions - Associate Professor of Physics, University of Tennessee and Principal Investigator UT/ORNL Accelerator Atomic Physics Group Oak Ridge National Laboratory, 1970-1974.

Research Physicist, Oak Ridge National Laboratory, 1967-1970.

Assistant Professor of Physics, New York University, 1965-1967.

Instructor, University of Chicago, 1964-1965.

Lecturer and Physicist, University of Chicago, 1961-1964, in the College and Laboratories for Applied Science.

Education - Undergraduate - Harvard College (Physics)
Graduate - University of Chicago (Physics)
S.M. - 1960; Ph.D. - 1964
Postdoctoral - University of Chicago (Enrico Fermi Institute)

Memberships - Fellow, American Physical Society, 1973 -

National Academy of Sciences, National Research Council Advisory Committee on Atomic and Molecular Science, 1973-1976.

Chairman, Publications Committee, 1974-76, Member, Program Committee, 1976-78, Am. Physical Society - Div. of Electron and Atomic Physics.

Chairman, Fourth International Conference on Beam-Foil Spectroscopy and Heavy Ion Atomic Physics Symposium, 1975.

Organizing and Advisory Committees, Third and Fourth Conferences on the Use of Small Accelerators, 1974-77.

Charter Committee, Holifield Heavy Ion Laboratory Users' Group, 1975.

PII Redacted

[redacted]

Awards - Organization of American States Guest Professor, Centro Atomico, Bariloche, Argentina, 1972.

Chancellor's Research Scholar's Prize, University of Tennessee, June, 1976.

Alexander von Humboldt Foundation Senior U. S. Scientist Award, 1977.

Awards - Senior Fulbright-Hays Grant, Fulbright-Hays program with Germany, 1977-78.

Awards - Swedish National Science Research Council and Nobel Institut, Gastprofessor, Forskningsinstitutet för Atomfysik, Stockholm, Sweeden, 1977-1978.

Other Professional Credits -

Editor and co-author of the following volumes:
Beam Foil Spectroscopy: Vol. 1, Atomic Structure and Lifetimes, Vol. 2 Collisional and Radiative Processes, with D. J. Pegg, Plenum Press, New York (1976).
Structure and Collisions of Ions and Atoms to be published by Springer-Verlag, Heidelberg, in 1978.

Chairman, American Physical Physical Society, Div. of Electron and Atomic Physics Annual Meeting, Knoxville, December, 1977.
Chairman and organizer of Symposia at the following American Physical Society meetings
"Symposium on Heavy Ion Atomic Physics," Winston-Salem, November, 1973.
"Symposium on The Use of High Energy Accelerators in Atomic Physics," Chicago, December, 1974.
"Symposium on Inner Shell Processes in Heavy Ion Atomic Collisions," Washington, April, 1975.
"Symposium on New Directions in Atomic Physics," Knoxville, June, 1975.
"Symposium on Heavy Ion Atomic Physics," Gatlinburg, September, 1975.
"Atomic Physics and Related Phenomena," Fourth Conference on Applications of Small Accelerators, Denton, October, 1976.

Chairman of other sessions at the following meetings:
American Physical Society, Washington, April, 1974.
Fourth International Conf. on Atomic Physics, Heidelberg, July, 1974.
American Physical Society, Washington, April, 1976.
Fifth International Conf. on Atomic Physics, Berkeley, July, 1976.
American Physical Society, Knoxville, December, 1977.

Grants and Contracts -

Principal Investigator, Office of Naval Research Contracts, 1972-present. Project Title: Structure of Highly Ionized Heavy Ions and Associated Collision Phenomena in the MeV/Nucleon Range.

Principal Investigator, National Aeronautics and Space Administration Grant 1972-3. Project Title: Ion Beam Experiments Related to Temperature and Densities in the Solar Corona.

Principal Investigator (with D. J. Pegg), National Science Foundation 1973-present. Project Title: Atomic Structure and Collision Experiments Concerning Core-Excited Atoms and Multiply Charged Heavy Ions.

Principal Investigator, National Aeronautics and Space Administration Grant 1973-present. Project Title: Line Identification and Lifetime Measurements in the XUV and Soft X-Ray Regions.

Principal Investigator, National Science Foundation, Office of Naval Research, and International Union of Pure and Applied Physics grants to the Fourth International Conference on Atomic Physics and Heavy Ion Atomic Physics Symposium, 1975.

Current Research -

The UT/ORNL heavy ion atomic physics research group is active in research on the atomic structure of collision and phenomena concerning highly ionized heavy ions. The research is presently being carried out at the Oak Ridge National Laboratory, the Brookhaven National Laboratory, the Gesellschaft für Schwerionen-Porschung, and occasional other sites. This group presently consists of three University of Tennessee faculty members, two postdoctoral research associates, two graduate students, and a number of occasional collaborators from other institutions whose participation is frequent. The primary objective of our research remains the study of atomic structure of highly ionized heavy ions and their modes of formation and destruction in collisions with target atoms and molecules. Decay of excited states of these ions by radiative and also by electron emission processes is the phenomenon we utilize in carrying out these experiments. Our principal tools are suitable heavy ion accelerators; x-ray, soft x-ray, and extreme ultraviolet spectrometers; electron spectrometers; and a variety of peripheral equipment associated with these devices.

Publications - Books

"Highly Ionized Ions," in Advances in Atomic and Molecular Physics, D. R. Bates and B. Bederson, eds., Academic Press, New York (1976), Vol. 12, p. 215.

"Measurement of Auger Lifetimes and Energy Levels by Projectile Electron Spectroscopy," in Topics in Current Physics, Vol. I: Beam Foil Spectroscopy, S. Bashkin, ed., Spinger-Verlag, Heidelberg (1976), Chap. 10, p. 265.

Beam Foil Spectroscopy: Vol. 1, Atomic Structure and Lifetimes, Vol 2, Collisional and Radiative Interactions, I. A. Sellin and D. J. Pegg, eds., Plenum Press, New York (1976).

Structure and Collisions of Ions and Atoms, I. A. Sellin, ed., Springer-Verlag, Heidelberg (1978); op. cit., "Extensions of Beam Foil Spectroscopy", Chap. 6.

Articles in Major Journals and Proceedings

"Production and Extinction of the 2S State of the Hydorgen Atom," Phys. Rev. 136, A1245 (1964).

"Lamb Shift in Li^{6++}," with C. Fan and M. Munoz, Phys. Rev. Lett. 15, 15 (1965).

"Binding Effects in Excitation by Heavy Charged Particles," with W. Brandt and R. Laubert, Phys. Lett. 21, 518 (1966).

"Characteristic X-Ray Production in Mg, Al, and Cu by Low-Energy Hydrogen and Helium Ions," with W. Brandt and R. Laubert, Phys. Rev. 151, 56 (1966).

"Energy Dependence of H(2s) Production in Proton-Alkali Collisions From 2 to 30 KeV," with L. Granoff, Phys. Lett. 25A, 484 (1967).

"Lamb Shift in the Li^{++} Ion," with C. Fan and M. Munoz, Phys. Rev. 161, 6 (1967).

"Progress in Producing Metastable States of One-Electron Heavy Ions," with B. Donnally, in Beam-Foil Spectroscopy, S. Bashkin, ed., Gordon and Breach, Science Publishers, New York (1968), p. 451.

"Experimental Transition Probabilities for Triplet-Singlet Transitions in Helium-like Heavy Ions," with B. Donnally and C. Fan, Phys. Rev. Lett. 21, 717 (1968).

"Periodic Intensity Fluctuations in Beam-Foil Excited Hydrogen," with C. D. Moak, P. M. Griffin, and J. A. Biggerstaff, in Physics of the One- and Two-Electron Atoms, F. Bopp and H. Kleinpoppen, eds., North-Holland Publishing Company, Amsterdam (1969), p. 387.

"Periodic Intensity Fluctuations of Balmer Lines from Single-Foil Excited Fast Hydrogen Atoms," with C. D. Moak, P. M. Griffin, and J. A. Biggerstaff, Phys. Rev. 184, 56 (1969)

"Stark-Perturbed Lyman Alpha Decay in Flight," with C. D. Moak, P. M. Griffin and J. A. Biggerstaff, Phys. Rev. 188, 217 (1969).

"Intensity Fluctuations of Light from Fast H Atoms: Addenda on Initial State Populations and Cascades," with J. A. Biggerstaff and P. M. Griffin, Phys. Rev. A1, 1553 (1970).

"Relative Orbital and Magnetic Substate Amplitudes in Single-Foil Excitation of Fast Hydrogen Atoms," with J. A. Biggerstaff and P. M. Griffin, Phys. Rev. A2, 423 (1970).

"Static Electromagnetic Fields as Probes of Ionic Fine Structure," Nucl. Instr. and Meth. 90, 329 (1970).

"Atomic Physics of Fast Ion Beams: Fine Structure Experiments," in Proceedings of the Second Oak Ridge Conference on Applications of Small Accelerators, J. Duggan, ed., USAEC CONF-700322, 289 (1970).

"Mean Life of the 2^3P_1 State of the Two-Electron Oxygen Ion," with B. Donnally, and W. W. Smith, Phys. Rev. A1, 1189 (1970).

"Comment on Relative Magnetic Substate Amplitudes in Single-Foil Excitation of Fast Hydrogen Atoms," Phys. Rev. A3, 1512 (1971).

"Lifetimes of the Metastable Autoionizing $(1s2s2p)^4P_{5/2}$ States of Lithium-like F^{6+} and O^{5+} Ions," with B. Donnally W. W. Smith, D. J. Pegg, and M. D. Brown, Phys. Rev. A4, 122 (1971).

"Collisional Excitation of Metastable Autoionizing States of Lithium-like Ions in Fast Beams: Spectra and Yields," with W. W. Smith, M. D. Brown, D. J. Pegg, and B. Donnally, in Proceedings of the Seventh International Conference on the Physics of Electronic and Atomic Collisions, North Holland Publishing Co., Amsterdam, p. 513 (1971).

"Spectra of Autoionization Electrons Emitted by Fast, Metastable Beams of Highly Stripped Oxygen and Fluorine Ions," with W. W. Smith, D. J. Pegg, M. D. Brown, and B. Donnally, Phys. Rev. Lett. 27, 1108 (1971).

"Time Dependent Theory of Stark Quenching of Metastable Hydrogen and Helium Atoms," with Helen K. Holt, Phys. Rev. A6, 508 (1972).

"Autoionization of Atoms Produced in Heavy Ion Collisions," in Proceedings of the ORNL Heavy-Ion Summer Study, Oak Ridge, Tennessee, AEC CONF-720669, 551 (1972).

"Metastable Autoionizing States of Highly Excited Heavy Ions," with D. J. Pegg, P. M. Griffin, and W. W. Smith, Phys. Rev. Lett. 28, 1229 (1972).

"Metastable Autoionizing States in Sodium-like Chlorine," with D. J. Pegg, P. M. Griffin, and W. W. Smith, Phys. Rev. Lett. 28, 1615 (1972).

"Equilibrium Fractions for the lowest Metastable Quartet States of Lithium-like Oxygen and Fluorine Ions Traversing Carbon Foils," with B. Donnally, W. W. Smith, D. J. Pegg, and M. D. Brown, Phys. Rev. A7, 487 (1973).

"Metastable States of Highly Excited Heavy Ions," with D. J. Pegg, P. M. Griffin, W. W. Smith, and B. Donnally, in Atomic Physics 3, Plenum Press, London, p. 327 (1973).

"Projectile Structure Effects on Neon K X-Ray Production by Fast, Highly Ionized Argon Beams," with J. R. Mowat, P. M. Griffin, D. J. Pegg, and R. S. Peterson, Phys. Rev. Lett. 29, 1577 (1972).

"Exponential Projectile Charge Dependence of Ar K and Ne K X-Ray Production by Fast, Highly Ionized Argon Beams in Thin Neon Targets," Proceedings of the Eighth International Conference on the Physics of Electronic and Atomic Collisions, B. Cobic and M. Kurepa, eds., Graficko Preduzece Buducnost, Zrenjanin, Yugoslavia (July, 1973), p. 727.

"Heavy Ions - Looking Ahead," with J. H. Hamilton, Physics Today 26, No. 4, 42 (1973).

"Mean Life of the Metastable 2^3P_1 State of the Two-Electron Fluorine Ion," with J. R. Mowat, R. S. Peterson, D. J. Pegg, M. D. Brown, and J. R. MacDonald, Phys. Rev. A8, 145 (1973).

"Electron Spectroscopy of Foil-Excited Chlorine Beams," with D. J. Pegg, P. M. Griffin, and W. W. Smith, Nucl. Instr. and Meth. 110, 489 (1973).

"Metastable Autoionizing States," Nucl. Instr. and Meth. 110, 477 (1973).

"Exponential Projectile Charge Dependence of Ar K and Ne K X-Ray Production by Fast, Highly-Ionized Argon Beams in Thin Neon Targets," with J. R. Mowat, D. J. Pegg, R. S. Peterson, J. R. MacDonald, and M. D. Brown, Phys. Rev. Lett. 30, 1289 (1973).

"One- and Two-Electron Excited States Producted by Electron Exchange, Excitation, and Electron Capture in Collisions of Fluorine Ions in Argon Gas at 34.8 MeV ," with J. R. Macdonald, P. Richard, C. L. Cocke, and M. D. Brown, Phys. Rev. Lett. 31, 684 (1973).

"Electron Decay-In-Flight Spectra for Autoionizing States of Highly Stripped Oxygen, Fluorine, Chlorine, and Argon Ions," with D. J.Pegg, R. S. Peterson, J. R. Mowat, W. W. Smith, J. R. Macdonald, and M. D. Brown, Phys. Rev. A8, 1350 (1973).

"Observation of Coherent Electron Density Distribution Oscillations in Collision-Averaged Foil Excitation of the n=2 Hydrogen Levels," with J. R. Mowat, R. S. Peterson, P. M. Griffin, R. Laubert, and H. H. Haselton, Phys. Rev. Lett. 31, 1335 (1973).

"Projectile Charge State Dependence of K X-Ray Production by 1-4 MeV/amu Heavy Ions in Gases," with J. R. Mowat, P. M. Griffin, D. J. Pegg, and R. S. Peterson, Phys. Rev. A9, 644 (1974).

"Initial UNISOR Research: New Isotopes ^{186}Tl, ^{188}Tl, ^{116}I; Decays of $^{189,190}Tl$, ^{117}Xe, and ^{117}I; and Off-Line Atomic and Nuclear Studies," published in the Proceedings of the Twenty-fourth Annual National Conference of the Academy of Science USSR on Nuclear Spectroscopy and Structure of the Atomic Nucleus, (1974).

"Observation of K X-Rays from Highly Ionized States of Neon Produced by 40 MeV Cl^{+7}, Cl^{+11}, and Cl^{+13} Beams," with M. D. Brown, J. R. Macdonald, P. Richard and J. R. Mowat, Phys. Rev. A9, 1470 (1974).

"Charge State Dependence of Si K X-Ray Production in Solid and Gaseous Targets by 40 MeV Oxygen Ion Impact," with S. Datz, J. R. Mowat, B. R. Appleton, J. A. Biggerstaff, and C. D. Moak, in Atomic Collions in Solids, S. Datz, ed., p. 461 (1975).

"Lifetime and Binding Energy of the Metastable $(1s2s2p)^4P^0_{5/2}$State in S^{13+}," with D. J. Pegg, H. H. Haselton, P. M. Griffin, R. Laubert, J. R. Mowat, and R. Peterson, Phys. Rev. A9, 1112 (1974).

"Neon Kα, Kβ Satellite Structure Induced by 80-MeV Argon-Ion Impact, " with J. R. Mowat, R. Laubert, R. L. Kauffman, M. D. Brown, J. R. Macdonald, and P. Richard, Phys. Rev. A10, 1446 (1974).

"Radiative Transitions in Two-electron Oxygen, " with D. J. Pegg, P. M. Griffin, H. H. Haselton, R. Laubert, J. R. Mowat, R. S. Thoe, and R. S. Peterson, Physics Letters 47A, 433 (1974).

"New Lines in the XUV Spectrum of Heliumlike Fluorine," with D. J. Pegg, P. M. Griffin, H. H. Haselton, R. Laubert, J. R. Mowat, R. S. Thoe, and R. S. Peterson, Physics Letters 47A, 467 (1974).

"XUV Spectra of Highly Ionized Fluorine and Oxygen," with D. J. Pegg, P. M. Griffin, H. H. Haselton, R. Laubert, J. R. Mowat, R. S. Thoe, and R. S. Peterson, Phys. Rev. A10, 745 (1974).

"Autoionization Lifetimes of the Metastable $(1s2s2p)^4P_{5/2}$ State in the Lithiumlike Ions Al^{10+}, Si^{11+}, and S^{13+}," with H. H. Haselton, R. S. Thoe, P. M. Griffin, J. R. Mowat, D. J. Pegg, and R. Peterson, published in the Proceedings of the Fourth International Conference on Atomic Physics, G. Zu Putlitz ed., Heidelberg, University Press, p. 79 (1974).

"Characterization of Charge States of Energetic Ions in Solids from Associated K X-Ray Production," with Sheldon Datz, B. R. Appleton, J. R. Mowat, R. Laubert, R. S. Peterson, and R. S. Thoe, Phys. Rev. Lett. 33, 733 (1974).

"Metastable Atomic States of Heavy Ions I: X-Ray Emitting States; II: X-Ray and Auger Emitting States; III: Auger Emitting States and Astrophysical Topics:, Vol. II, Heavy Ion Lecture Series, Kansas State University, pp. 329, 352, and 380, respectively (1974). The other lecturers in this series were D. Allan Bromley, Eugen Merzbacher, Donald Robson, Frans Saris, H. Terry Fortune, J. D. Garcia and Walter Greiner.

"Symmetric Ion Atom Collisions at Medium Energies I: Characteristic X-Rays," with R. Laubert, H. Haselton, J. R. Mowat, and R. S. Peterson, Phys. Rev. A11, 135 (1975).

"Observation of Large and Strongly Energy Dependent Directional Anisotropies in Non-Characteristic K X-Rays Emitted in Heavy Ion Collisions," with R. S. Thoe, R. Peterson, P. M. Griffin, D. J. Pegg, J. P. Forester, and M. D. Brown, Phys. Rev. Lett. 34, 64 (1975).

"Projectile Electron Emission Spectroscopy on Optically Inaccessible Autoionizing States in the Alkali Metals," with D. J. Pegg, H. H. Haselton, R. S. Thoe, R. Peterson, M. D. Brown, and W. W. Smith, Phys. Lett. 50A, 447 (1975).

"Variation of the Anisotropy of the Non-Characteristic X-Rays Emitted from Fast Ion-Atom Collisions," with R. S. Thoe, R. Peterson, P. M. Griffin, D. J. Pegg, J. P. Forester, and M. D. Brown, in Proceedings of the Third Conference on Applications of Small Accelerators, ERDA CONF-741040P1, p. 78 (1975).

"Lifetimes of the Metastable Autoionizing $(1s2s2p)^4P_{5/2}$ States of Lithiumlike Al^{10+} and Si^{11+} Ions: *Comparisons with Theory over the Isoeletronic* Sequence Z = 8 - 18," D. J. Pegg, P. M. Griffin, H. H. Haselton, R. Laubert, J. R. Mowat, R. S. Thoe, R. S. Peterson, and I. A. Sellin, Phys. Rev. A 11, 468 (1975).

"Symmetric Ion-Atom Collisions at Medium Energies: Non-Characteristic Radiation," with R. Laubert, H. H. Haselton, J. R. Mowat, and R. S. Peterson, Phys. Rev. A11, 1468 (1975).

"Heliumlike ^{19}F; 2^3P_2 and 2^3P_0 Lifetimes," with J. R. Mowat, P. M. Griffin, H. H. Haselton, R. Laubert, D. J. Pegg, R. S. Peterson, and R. S. Thoe, Phys. Rev. A11, 2198 (1975).

"Photon Energy Dependence of the Asymmetry of Non-Characteristic X-Radiation in Si-Al and Al-Al Collisions," with R. S. Thoe, R. S. Peterson, D. J. Pegg, P. M. Griffin, and J. P. Forester, in Electronic and Atomic Collisions, J. S. Risley and R. Geballe, eds., Univ. of Washington Press, Seattle, p. 312 (1975).

"Autoionizing States Formed in Na^+ + He and Mg^+ + He Collisions at 70 KeV," with D. J. Pegg, H. H. Haselton, R. S. Thoe, P. M. Griffin, and M. D. Brown, in Electronic and Atomic Collisions, R. S. Risley and R. Geballe, eds., Univ. of Washington Press, Seattle, p. 869 (1975).

"Differences in the Production of Non-Characteristic Radiation in Solid and Gas Targets," with R. S. Peterson, R. Laubert, R. S. Thoe, H. Hayden, S. Elston, J. Forester, K.-H. Liao, P. M. Griffin and D. J. Pegg, in Beam-Foil Spectroscopy: Heavy Ion Atomic Physics, I. A. Sellin and D. J. Pegg, eds., Plenum Press, New York (1976), Vol. 2, p. 497.

"Extreme Ultraviolet Spectra of Highly Stripped Si Ions," with P. M. Griffin, D. J. Pegg, T. Kruse, K. W. Jones, D. Pisano, and S. Bashkin, in Beam-Foil Spectroscopy: Heavy Ion Atomic Physics, I. A. Sellin and D. J. Pegg, eds., Plenum Press, New York (1976), Vol. I, p. 321.

"Angular Distribution Studies on Non-Characteristic X-Radiation," with R. S. Thoe, K.-H. Liao, R. S. Peterson, D. J. Pegg, J. P. Forester, and P. M. Griffin, in Beam-Foil Spectroscopy: Heavy Ion Atomic Physics, I. A. Sellin and D. J. Pegg, eds., Plenum Press, New York (1976), p. 477.

"Autoionizing States in Highly Ionized O, F. and Si," with J. P. Forester, R. S. Peterson, P. M. Griffin, H. Haselton, K.-H. Liao, J. R. Mowat, D. J. Pegg, and R. S. Thoe, in Beam-Foil Spectroscopy: Heavy Ion Atomic Physics, I. A. Sellin and D. J. Pegg, eds., Plenum Press, New York (1976), Vol. 1, p. 451.

"Core-Excited Autoionizing States in the Alkalis," with D. J. Pegg, H. H. Haselton, R. S. Thoe, P. M. Griffin, and M. D. Brown, Phys. Rev. A 12, 1330 (1975).

"Applications of Beam-Foil Spectroscopy to Atomic Collisions in Solids," Nucl. Inst. and Meth. 132, 397 (1976).

"Polarization Measurements on the Non-characteristic Radiation Emitted from Collisions Between High Energy Aluminum Ions," with R. S. Thoe, R. S. Peterson, K-H. Liao, D. J. Pegg, J. P. Forester, and P. M. Griffin, Phys. Letters 56A, 89 (1976).

"Differences in the Production of Non-characteristic Radiation in Gaseous and Solid Targets," with R. Laubert, R. S. Peterson, J. P. Forester, K-H. Liao, P. M. Griffin, H. Hayden, S. A. Elston, D. J. Pegg, and R. S. Thoe, Phys. Rev. Lett. 36, 1574 (1976).

"Lifetimes and Transition Rates for Allowed In-Shell Transitions in Highly Stripped Sulfur," with D. J. Pegg, S. B. Elston, J. P. Forester, P. M. Griffin, H. C. Hayden, R. S. Peterson, and R. S. Thoe, in Proceedings of the Fifth International Conference on Atomic Physics, R. Marrus, M. H. Prior, and H. A. Shugart, eds., University of California, Berkeley, Calif. (1976) p. 166.

"An Experimental Survey of Electron Transfer in keV Collisions in Multiply Charged Ions with Atomic Hydrogen," with J. E. Bayfield, P. M. Koch, L. D. Gardner, D. J. Pegg, R. S. Peterson, and D. J. Crandall, in Proceedings of the Fifth International Conference on Atomic Physics, R. Marrus, M. H. Prior, and H. A. Shugart, eds., University of California, Berkeley, Calif. (1976) p. 126.

"Radiative Lifetimes and Transition Probabilities for Electric Dipole $\Delta n=0$ Transitions in Highly Stripped Sulfur Ions," with D. J. Pegg, S. B. Elston, P. M. Griffin, H. C. Hayden, J. P. Forester, R. S. Thoe, and R. S. Peterson, Phys. Rev. A 14, 1036 (1976).

"Dipole Oscillator Strengths for $\Delta n=0$ Transitions in Highly Ionized Sulfur," with D. J. Pegg, S. B. Elston, P. M. Griffin, H. C. Hayden, J. P. Forester, R. S. Thoe, and R. S. Peterson, Physics Lett. 58A, 349 (1976).

"Charge Dependence of K X-Ray Production in Nearly Symmetric Collisions of Highly Ionized S and Cl Ions in Gases," with J. R. Macdonald, M. D. Brown, S. J. Czuchlewski, L. M. Winters, R. Lauberts, and J. R. Mowat, Phys. Rev. A14, 1997 (1976).

"Strong Isotope Dependence of K-Vacancy Production in Slow Ne^{+}-Ne Collisions," with R. S. Peterson, S. B. Elston, R. Laubert, F. K. Chen, and C. A. Peterson, Phys. Rev. Lett. 37, 984 (1976).

"Projectile Charge-State Dependence in K-Shell Ionization of Neon, Silicon, and Argon Gases by Lithium Projectiles," with F. K. Chen, G. Lapicki, R. Laubert, S. B. Elston, and R. S. Peterson, Physics Lett. 60A, 292 (1977).

"Overcoming the Doppler Limitation in Beam-Foil Experiments by Target Ion Spectroscopy," in Proceedings, Fourth Conference on Scientific and Industrial Applications of Small Accelerators, J. L. Duggan and I. L. Morgan, eds. (International Association of Electrical and Electronic Engineers, Report 76 CH 1175-9 NPS, New York), p. 319 (1977).

"Production of Soft X-Ray Emitting Slow Multiply Charged Ions: Recoil Ion Spectroscopy," with S. B. Elston, J. P. Forester, P. M. Griffin, D. J. Pegg R. S. Peterson, R. S. Thoe, C. R. Vane, and J. J. Wright, Phys. Lett. 61A 107 (1977).

"The Splitting and Oscillator Strengths for the $2s^2S$-$2p^2P^0$ Doublet in Lithiumlike Sulfur," with D. J. Pegg, J. P. Forester, S. B. Elston, P. M. Griffin, K. -O. Groeneveld, R. S. Peterson, R. S. Thoe, and C. R. Vane, Astrophysical J. 214, 331 (1977).

"Oscillator Strengths for In-shell ($\Delta n = 0$) Dipole Transitions in Li- and Be-like Sulfur," with D. J. Pegg, J. P. Forester, C. R. Vane, S. B. Elston P. M. Griffin K. -O. Groeneveld , R. S. Peterson, and R. S. Thoe, Phys. Rev. A15 1958 (1977).

"Neon Characteristic X-ray Production in Neon-Neon Collisions as a Function of Incident Projectile Charge State", with R. S. Peterson, F. J. Chen, S. B. Elston, J. P. Forester, P. M. Griffin, H. C. Hayden, R. Laubert, C. A. Peterson R. S. Thoe, and C. R. Vane in Proceedings, Tenth International Conference on the Physics of Electronic and Atomic Collisions, M. Barat, J. Reinhardt, and G. Watel, eds. (Commissariat a l'Energie Atomique, Paris), p. 894 (1977).

"Spin-dependent Excitation of Autoionizing States of Li Produced in Collisions with Noble Gas Targets", with S. Schumann, S. B. Elston, C. R. Vane, J. P. Forester, P. M. Griffin, D. J. Pegg, R. S. Thoe, and J. J. Wright, in Proceedings Tenth International Conference on the Physics of Electronic and Atomic Collisions, M. Barat, J. Reinhardt, and G. Watel, eds. (Commissariat a l'Energie Atomique, Paris), p. 1014 (1977).

"Recoil Ion Spectroscopy in the XUV-Soft X-Ray Region Following Heavy Ion Impact on Thin Gas Targets," with S. B. Elston, J. P. Forester, P. M. Griffin D. J. Pegg, R. S. Peterson, R. S. Thoe, C. R. Vane, and J. J. Wright, in Proceedings, Tenth International Conference on the Physics of Electronic and Atomic Collisions, M. Barat, J. Reinhardt, and G. Watel, eds. (Commissariat a l'Energie Atomique, Paris), p. 634 (1977).

"High Resolution Studies of Extensive Ne L-Shell Excitation by Energetic Heavy Ion Impact," with S. B. Elston, J. P. Forester, P. M. Griffin, D. J. Pegg, R. S. Peterson, R. S. Thoe, C. R. Vane, and J. J. Wright, in Proceedings, Tenth International Conference on the Physics of Electronic and Atomic Collisions, M. Barat, J. Reinhardt, and G. Watel, eds. (Comissariat a l'Energie Atomique, Paris), p. 632 (1977).

"Observation of Quantum Beats in Gas-excited Helium Projectiles", with J. Bromander and L. Liljeby, submitted to Zeitschrift für Physik, 1977.

"Studies of Neon L-Shell Excitation by Impact of Highly Ionized Heavy Ions," with C. R. Vane, S. B. Elston, J. P. Forester, P. M. Griffin, D. J. Pegg, and R. S. Thoe, to be published in Zeitschrift für Physik, 1977

"The Violent Many-Electron Chemistry of Highly Charged Ions", to be published in Physics News - 1977, G. Present, ed. (American Institute of Physics, New York), 1977.

Contributed Papers:

"Stark Quenching of Metastable 2S Hydrogen Atoms," Bull. Am. Phys. Soc. 9, 150 (1964).

"Comparative K-Shell X-Ray Production in Aluminum by Low-Energy Protons and Helium Ions," with W. Brandt, and R. Laubert, Bull. Am. Phys. Soc. 11, 389 (1966).

"Lamb Shift in $(Li^6)^{++}$," with C. Fan and M. Munoz, Bull. Am. Phys. Soc. 11, 748 (1966).

"Cross Sections for Production of H(2S) in Proton-Cesium Collisions in the Range 2 to 25 KeV," with L. Granoff, Bull. Am. Phys. Soc. 12, 748 (1966).

"Velocity Dependence of H(2S) Production for H^+ on Cs, Rb, and K in the Range 2 to 30 KeV," with L. Granoff, Bull. Am. Phys. Soc. 12, 1044 (1967).

"Periodic Intensity Fluctuations in Beam-Foil Excited Hydrogen," with C. D. Moak, J. A. Biggerstaff, and P. M. Griffin, Symposium on the Physics of One- and Two-Electron Atoms, Universitat Munchen, Munchen, West Germany, September, 1968.

"Measurement of Singlet-Triplet Transition Probabilities in Two-Electron Heavy Ions," with B. Donnally and C. Fan, presented at the Symposium on the Physics of One- and Two-Electron Atoms, Universitat Munchen, Munchen, West Germany, September, 1968.

"Soft X-Rays from Stripped Oxygen Beams," with B. Donnally, Bull. Am. Phys. Soc. 14, 733 (1969).

"Periodic Intensity Fluctuations of Balmer Lines from Single-Foil Excited Fast Hydrogen Atoms," with C. D. Moak, P. M. Griffin, and J. A. Biggerstaff, Bull. Am. Phys. Soc. 14, 630 (1969).

"Time Dependent Intensity Fluctuations in Light Emitted in Atoms," with C. D. Moak, P. M. Griffin, and J. A. Biggerstaff, in USAEC Fundamental Nuclear Energy Research (1969), Washington, D. C. (1970), supp., p. 197.

"Measurement of the Total Transition Probability for the 2^3P_1 State of O^{6+}," with B. Donnally, M. D. Brown, and W. W. Smith, Bull. Am. Phys. Soc. 15, 57 (1970).

"Influence of Field Geometry on Lyα Polarization Corrections to H(n=2) Cross Sections Established by the Stark Quenching Method," with D. J. Pegg, Bull. Am. Phys. Soc. 15, 1523 (1970).

"Inner Shell Excitation Cross Sections for Iodine and Silver in Collision," with R. Laubert, S. Datz, C. D. Moak, and B. R. Appleton, Bull. Am. Phys. Soc. 16, 79 (1971).

"Observation of Stark Quenching of the 2S State of O^{7+}," with W. W. Smith, M. D. Brown, D. J. Pegg, and B. Donnally, Bull. Am. Phys. Soc. 16, 79 (1971).

"Autoionization Lifetimes of the Lowest Metastable Quartet States in Fast Beams of Lithium-like F^{6+} and O^{5+} Ions," with D. J. Pegg, M. D. Brown, W. W. Smith, and B. Donnally, Bull. Am. Phys. Soc. 16, 106 (1971).

"Collisional Excitation of Metastable Autoionizing States of Lithium-like Ions in Fast Beams: Spectra and Yields," with W. W. Smith, M. D. Brown, D. J.Pegg, and B. Donnally, Presented at the Seventh International Conference on the Physics of Electronic and Atomic Collisions, Amsterdam, July, 1971.

"Metastable States of Highly Excited Heavy Ions," with D. J. Pegg, P. M. Griffin, W. W. Smith, and B. Donnally, Presented at the Second International Conference on Atomic Physics, Boulder, Colorado, August, 1972.

"Electron Spectroscopy of Foil-Excited Chlorine Beams," with D. J. Pegg, P. M. Griffin, and W. W. Smith, presented at the Third International Conference on Beam-Foil Spectroscopy, Tucson, Arizona, October, 1972.

"Mean Life of the Metastable 2^3P_1 State of the Two-Electron Fluorine Ion," with J. R. Mowat, R. S. Peterson, D. J. Pegg, J. R. Macdonald, M. D. Brown, Bull. Am. Phys. Soc. 18, 610 (1973).

"Exponential Projectile Charge Dependence of Ar K and Ne K X-Ray Production by Fast, Highly Ionized Argon Beams in Thin Neon Targets," with J. R. Mowat, D. J. Pegg, R. S. Peterson, J. R. Macdonald and M. D. Brown, presented at the Eighth International Conference on the Physics of Electronics and Atomic Collisions, Belgrad, Yugoslovia, July, 1973.

"Electron Spectra from the Decay-in-Flight of Metastable Autoionizing States Associated with Highly Excited Heavy Ions," with D. J. Pegg, R. Peterson, and J. R. Mowat, Bull. Am. Phys. Soc. 18, 1527 (1973).

"Binding Energy and Lifetime of the $(1s2s2p)^4P^0{}_{5/2}$ State in Lithiumlike Sulfur," with H. Haselton, D. J. Pegg, P. M. Griffin, R. Laubert, J. R. Mowat, and R. Peterson, Bull. Am. Phys. Soc. 18, 1527 (1973).

"Projectile Structure Effects in Heavy-Ion-Induced K X-Rays: Target X-Rays," with J. R. Mowat, P. M. Griffin, D. J. Pegg, and R. S. Peterson, Bull. Am. Phys. Soc. 18, 1508 (1973).

"Projectile Structure Effects in Heavy-Ion-Induced K X-Rays: Projectile X-Rays," with J. R. Mowat, P. M. Griffin, D. J. Pegg, and R. S. Peterson, Bull. Am. Phys. Soc. 18, 1508 (1973).

"Effective Charge State of Heavy Ions Penetrating Solids Deduced from Comparing X-Ray Yields in Gases and Solids," with S. Datz, J. R. Mowat, B. Appleton, J. A. Biggerstaff, and C. D. Moak, Bull. Am. Phys. Soc. 18, 1508 (1973); presented at the Third International Conference on Atomic Collisions in Solids, Gatlinburg, Tennessee, September, 1973.

"Observation of Coherently Excited Dipole Charge Distribution Oscillations in Collision-Averaged Foil Excitation of the n=2 H Levels," with R. S. Peterson, J. R. Mowat, P. M. Griffin, H. Haselton, and R. Laubert, Bull. Am. Phys. Soc. 18, 1527 (1973).

"Observation of K X-Rays from Highly Ionized States of Neon Produced by 40 MeV Cl^{+7}, Cl^{+11}, and Cl^{+13} Beams," with M. D. Brown, J. R. MacDonald, P. Richard, and J. R. Mowat, Bull. Am. Phys. Soc. 19, 89 (1974).

"XUV Spectra of Highly Stripped Oxygen and Fluorine," with D. J. Pegg, P. M. Griffin, H. H. Haselton, R. Laubert, J. R. Mowat, R. S. Thoe, and R. S. Peterson, Bull. Am. Phys. Soc. 19, 469 (1974).

"Improvements in the Use of Grazing Incidence Spectrometers to Study Spectra of Low Intensity, Highly Stripped Ion Beams," with P. M. Griffin, R. S. Thoe, H. H. Haselton, R. Laubert, R. S. Peterson, J. R. Mowat, and D. J. Pegg, Bull. Am. Phys. Soc. 19, 469 (1974).

"Ne and Ar K X-Ray Satellite Production," with J. R. Mowat, R. Laubert, M. D. Brown, R. L. Kauffman, J. R. MacDonald, and P. Richard, Bull. Am. Phys. Soc. 19, 570 (1974).

"K X-ray Yields from Single Collisions of ~100 MeV Cl Ions with Si ," with S. J. Czuchlewski, M. D. Brown, J. R. MacDonald, L. M. Winters, R. Laubert, and J. R. Mowat, Bull. Am. Phys. Soc. 19, 590 (1974).

"n=2 Finestructure Decays in He-like F," with J. R. Mowat, P. M. Griffin, R. S. Peterson, H. H. Haselton, R. Laubert, D. J. Pegg, and R. S. Thoe, Bull. Am. Phys. Soc. 19, 468 (1974).

"Charge State Dependent Energy Shifts of K X-ray Accompanying Nearly Symmetric Collisions of 3 MeV/amu S and Cl Ions," with R. Laubert, J. R. Mowat, M. D. Brown, S. Czuchlewski, J. R. MacDonald, and L. Winter, Bull. Am. Phys. Soc. 19, 590 (1974).

"X-Ray Cross Sections in Symmetric Ion-Atom Collisions," with J. R. Mowat, R. Laubert, H. Haselton, and R. S. Peterson, Bull. Am. Phys. Soc. 19, 570 (1974).

"Observations of Non-Characteristic Combined Atom K-Shell X-Ray Band in Al-Al Collisions," with R. Laubert, H. Haselton, J. R. Mowat, and R. S. Peterson, Bull. Am. Phys. Soc. 19, 590 (1974).

"Autoionization Lifetimes of the Metastable $(1s2s2p)^4P_{5/2}$ State in the Lithium-like Ions Al^{10+}, Si^{11+}, and S^{13+}," with H. H. Haselton, R. S. Thoe, P. M. Griffin, J. R. Mowat, D. J. Pegg, and R. Peterson, presented at the Fourth International Conference on Atomic Physics, Heidelberg, West Germany, July, 1974.

"Lifetimes and Binding Energies of the Metastable Autoionizing $(1s2s2p)^4P_{5/2}$ State in Al^{10+} and Si^{11+}," with R. S. Thoe, H. H. Haselton, P. M. Griffin, J. R. Mowat, R. S. Peterson, and D. J. Pegg, Bull. Am. Phys. Soc. 19, 1176 (1974).

"Characterization of Charge States of Energetic Ions in Solids from Associated K X-Ray Production," with S. Datz, B. R. Appleton, J. R. Mowat, R. Laubert, R. S. Peterson, and R. S. Thoe, Bull. Am. Phys. Soc. 19, 1184 (1974).

"Electron Spectroscopy of Autoionizing States in LiI and NaI," with D. J. Pegg, H. H. Haselton, M. D. Brown, R. S. Thoe, P. M. Griffin, and W. W. Smith, Bull. Am. Phys. Soc. 19, 1184 (1974).

"Energy Dependence of the Directional Anisotropy Exhibited by Quasimolecular K X-Radiation," with R. S. Thoe, M. D. Brown, J. P. Forester, P. M. Griffin, D. J. Pegg, and R. S. Peterson, Bull. Am. Phys. Soc. 20, 75 (1975).

"Charge State Dependence of X-Ray Production of Collisions of Ni ($\sim$ 1 MeV/amu) with SiH_4," with S. Datz, M. D. Brown, P. M. Griffin, R. S. Peterson, and R. S. Thoe, Bull. Am. Phys. Soc. 20, 639 (1975).

"Electron Spectra from the Autoionizing Decay of Collisionally Excited Mg^+ and K^+ Beams," with D. J. Pegg, H. H. Haselton, M. D. Brown, R. S. Thoe, and P. M. Griffin, Bull. Am. Phys. Soc. 20, 674 (1975).

"Non-Characteristic Spectra from Symmetric and Asymmetric Collision Systems," with R. S. Thoe, D. J. Pegg, J. P. Forester, K.-H. Liao, R. S. Peterson, and P. M. Griffin, Bull. Am. Phys. Soc. 20, 675 (1975).

"Electron Spectra from Autoionizing States of Highly Stripped Oxygen and Fluorine," with R. S. Peterson, J. P. Forester, P. M. Griffin, H. H. Haselton, K.-H. Liao, J. R. Mowat, D. J. Pegg, and R. S. Thoe, Bull. Am. Phys. Soc. 20, 679 (1975).

"Autoionizing States in Lighiumlike Si and Sodiumlike Cl," with J. P. Forester, P. M. Griffin, H. H. Haselton, K.-H. Liao, J. R. Mowat, D. J. Pegg, R. S. Peterson, and R. S. Thoe, Bull. Am. Phys. Soc. 20, 679 (1975).

"Beam-Foil Spectra of Iron, Copper, and Silicon, with S. Bashkin, J. A. Leavitt, K. W. Jones, D. Pisano, T. Kruse, P. Griffin, and D. Pegg, Bull. Am. Phys. Soc. 20, 1452 (1975).

"Comparison of Production of Non-Characteristic X-Ray Radiation in Solid (Al) and Gaseous (SiH_4) Targets," with R. Peterson, R. Laubert, R. S. Thoe, H. Hayden, S. Elston, J. Forester, K-H. Liao, P. M. Griffin, and D. J. Pegg, Bull. Am. Phys. Soc. 20, 1450 (1975).

"Characteristic K X-Ray Production from High Energy Al-Al Collisions," with R. S. Thoe, J. P. Forester, R. S. Peterson, D. J. Pegg, P. M. Griffin, and K-H. Liao, Bull. Am. Phys. Soc. 21, 640 (1976).

"Beam-foil Radiative Lifetime Measurements in SiIX-SiXII," with D. J. Pisano and K. W. Jones of Brookhaven National Lab, P. M. Griffin and D. J. Pegg of O.R.N.L., T. Kruse of Rutgers, and S. Bashkin of the University of Arizona, Bull. Am. Phys. Soc. 21, 689 (1976).

"Lifetimes and Spectra of Highly Ionized Sulfur," with S. B. Elston, D. J. Pegg, P. M. Griffin, J. P. Forester, H. C. Hayden, R. S. Peterson, and R. S. Thoe, Bull. Am. Phys. Soc. 21, 626 (1976).

"Radiative Electron Capture Cross Sections for High Energy Al-Al and Al-C Collisions," with R. S. Thoe, J. P. Forester, D. J. Pegg, R. S. Peterson and K-H. Liao, Bull. Am. Phys. Soc. 21, 650 (1976).

"Single and Double Electron Transfer in B^{q+} (q = 2,3,4) Collisions with He, Ar, and H_2," with J. E. Bayfield, P. M. Koch, L. D. Gardner, D. J. Pegg, R. S. Peterson, D. H. Crandall, and M. L. Mallory, Bull. Am. Phys. Soc. 21, 549 (1976).

"An Experimental Survey of Electron Transfer in keV Collisions of Multiply Charged Ions with Atomic Hydrogen," with J. E. Bayfield, P. M. Koch, L. D. Gardner, D. J. Pegg, R. S. Peterson, and D. H. Crandall, presented at the Fifth International Conference on Atomic Physics, Berkeley, Calif., July, 1976.

"Lifetimes and Transition Rates for Allowed 'In-Shell' Transitions in Highly Stripped Sulfur," with D. J. Pegg, S. B. Elston, J. P. Forester, P. M. Griffin, H. C. Hayden, R. S. Peterson, and R. S. Thoe, presented at the Fifth International Conference on Atomic Physics, Berkeley, Calif., July, 1976.

"Radiative Lifetimes and Oscillator Strength for the n=2 States of Be-like Sulfur," with J. P. Forester, D. J. Pegg, S. B. Elston, P. M. Griffin, K.-O. Groeneveld, R. S. Peterson, R. S. Thoe, and C. R. Vane, Bull Am. Phys. Soc. 21, 1253 (1976).

"A Beam-Foil Study of the $2s^2S$-$2p^2P^o$ Doublet in Li-like Sulfur," with C. R. Vane, D. J. Pegg, S. B. Elston, J. P. Forester, P. M. Griffin, K.-O. Groeveneld, R. S. Peterson, and R. S. Thoe, Bull Am. Phys. Soc. 21, 1252 (1977).

"Mass Dependence of Ne K X-Ray Yields from Ne^+-Ne Collisions at keV Energies," with R. S. Peterson, S. B. Elston, R. Laubert, F. K. Chen, and C. A. Peterson, Bull. Am. Phys. Soc. 21, 1248 (1976).

"Measurement of the H^++H Charge Exchange Cross Section, 0.8-2.5 MeV," with L. D. Gardner, P. M. Koch, J. E. Bayfield, H. Hayden, R. Thoe, J. Forester, and D. J. Pegg, in Bull. Am. Phys. Soc. 21, 1265 (1977).

"Der $2s^2S$-$2p^2P^o$ Doublettübergang in Li-ähnlichem Schwefel," with C. R. Vane, D. J. Pegg, S. B. Elston, J. P. Forester, P. M. Griffin, K.-O. Groeneveld, and R. S. Thoe, Verhandl., Deutsche Physikalische Gesellschaft 2/1977, 500 (1977).

"Lebensdauern und Oszillatørenstärken von n=2 Zuständen in Be-ähnlichem S," with J. P. Forester, D. J. Pegg, S. B. Elston, P. M. Griffin, K.-O. Groeneveld, R. S. Peterson, R. S. Thoe, and C. R. Vane, Verhandl., Deutsche Physikalische Gesellschaft 2/1977, 500 (1977).

"An Application of the Beam Foil Method to Transitions of Astrophysical Interest," with D. J. Pegg, J. P. Forester, P. M. Griffin, C. R. Vane, S. B. Elston, R. S. Thoe, H. C. Hayden, K. O. Groeneveld, and R. S. Peterson, presented at the American Physical Society Topical Conference on Atomic Processes in High Temperature Plasmas, Knoxville, February, 1977.

"$\Delta n=0$ Transitions in Highly Ionized Ions," with D. J. Pegg, P. M. Griffin, S. B. Elston, J. P. Forester, K. O. Groeneveld, H. C. Hayden, R. S. Peterson, R. S. Thoe, and C. R. Vane, in Proceedings, Nordic Symposium on Atomic and Molecular Transition Probabilities, I. Martinson, ed. (Lunds Univeristet, Lund), p. 8 (1977).

"Production of Core-Excited States of Li and Li^{+} in Collisions with Gas Targets, with S. B. Elston, C. R. Vane, J. P. Forester, D. J. Pegg, and S. R. Schumann, Bull. Am. Phys. Soc. 22, 655 (1977).

"Projectile Charge-State Dependence in K-Shell Ionization of Neon, Silicon, and Argon Cases by Lithium Projectiles, with F. K. Chen, G. Lapicki, R. Laubert, S. B. Elston, and R. S. Peterson, Bull. Am. Phys. Soc. 22, 655 (1977).

"Lower Limits on Resolved Neon L-shell Excitation Cross-sections by Impact of 1.5 MeV/A $\sim S^{12+}$, Cl^{12+} Ions," with C. R. Vane, S. B. Elston, J. P. Forester, P. M. Griffin, D. J. Pegg, R. S. Peterson, R. S. Thoe, J. Wright, K. -O. Groeneveld, R. Laubert, and F. Chen, Bull Am. Phys. Soc. 22, 609 (1977).

"Recoil Ion Spectroscopy: Reduction of Doppler Shifts and Spreads in Fast Beam Experiments, with C. R. Vane, S. B. Elston, J. P. Forester, P. M. Griffin, D. J. Pegg, R. S. Peterson , R. S. Thoe, and K. -O. Groeneveld, Bull. Am. Phys. Soc. 22, 610 (1977).

"Measurement of Alignments in Single Ion-Atom Collisions by a Quantum Beat Method", with J. Bromander, L. Liljeby, and L. Lundin, presented at the Fourth International Seminar on Ion-Atom Collisions, Darmstadt, Germany, July, 1977.

"Target Specificity Effects on the Production of Core-Excited States of Li and Li^{+} for 10 to 50 keV Collisions of Li^{+} with Gas Targets", with S. B. Elston, C. R. Vane, J. P. Forester, P. M. Griffin, D. J. Pegg, S. Schumann, M. Suter and R. S. Thoe to be published in Bull. Am. Phys. Soc., November, 1977.

"Stark Shifts and Broadening of Auger Lines of Highly Ionized Atoms in Molecules After Heavy Ion Impact", with K. O. Groeneveld, D. Rosich, S. Schumann, and Gy. Szabo, to be published in Bull. Am. Phys. Soc., November, 1977.

"Quantum Beat Method of Measuring Alignments in Single Ion-Atom Collisions," with J. B. Bromander, L. Liljeby, and L. Lundin, to be published in Bull. Am. Phys. Soc., Nov. 1977.

"Metastable Auger Emitter Lifetimes by a Delayed Coincidence Technique," with R. Mann, H. J. Frischkorn, D. Rosich, S. Schumann, and Gy. Szabo, to be published in Bull. Am. Phys. Soc., Nov. 1977.

Invited Papers, Colloquia, and Seminars:

"Polarized Proton Production," Physics Department Colloquium, New York University, December, 1964. Also presented at Haverford College, December, 1964.

"Radiative Level Shifts in Hydrogen-like Ions," Physics Department Seminar, University of Chicago, May, 1965.

"X-Ray Production by Low-Energy Ion Impact," Atomic Physics Seminar, New York University, February, 1966.

"An Introduction to Quantum Electrodynamics," Sigma Pi Sigma Lecture, New York University, May,1966.

"Lamb Shift in Li^{++}," invited talk, Yale University Physics Department, November, 1966.

"Level Shifts in Lithium," Physics Department Colloquium, New York University, March 1967.

"Lamb Shift in Lithium and Prospects for Measurements in Hydrogen-like Atoms of Higher Z," Columbia Radiation Laboratory Resonance Seminar, Columbia University, May, 1967.

"One-, Two-, and Three-Electron Atoms with Boosted Nuclear Charge," Physics Division Seminar, Oak Ridge National Laboratory, May, 1969.

"Atomic Physics and Accelerators," Oak Ridge Associated Universities, Summer Institute for College Teachers, August, 1969.

"Impulsive Interference Effects in Atomic Fine Structure," Physics Department Colloquium, University of Connecticut, November 1969.

"Stark Coupling of Coherently Excited Fine Structure Levels," Physics Department Colloquium, University of Arkansas, December, 1969.

"Static Electromagnetic Fields as Probes of Ionic Fine Structure, Invited Paper, presented at the Second International Conference on Beam-Foil Spectroscopy, Lysekil, Sweden, June, 1970.

"Atomic Physics of Fast Ion Beams: Fine Structure Experiments," Invited Paper, presented at the Second Conference on the Use of Small Accelerators in Teaching and Research, Oak Ridge, March, 1970.

"Atomic Physics Accelerator Experiments at Oak Ridge," Invited Paper, presented at Southern Colleges and Universities Union (SCUU) Meeting, Vanderbilt University, August, 1970.

"Big Brothers of the Helium Negative Ion," Physics Department Colloquium, University of Tennessee, January, 1971.

"Coherent Excitation Experiments in Atomic Collisions," Atomic Physics Seminar, Bell Telephone Laboratories, Murray Hill, January, 1971.

"Recent Ion Beam Atomic Physics Experiments at Oak Ridge,"Atomic Physics Seminar, Physics Department, University of Massachusetts, January, 1971.

"Atomic Physics of Fast Ion Beams: Fine Structure Experiments II," Invited Paper, Oak Ridge Associated Universities, Summer Institute of College Teachers, July, 1971

"New Results in Atomic Spectroscopy Using Fast Ionic and Atomic Beams," Invited Paper, presented in the Annual Meeting of the Division of Electron and Atomic Physics of the American Physical Society, Bull. Am. Phys. Soc. 16, 1356 (1971).

"Metastable Autoionizing States of Highly Stripped and Excited Ion Beams," Radiation Laboratory Seminar, New York University, December, 1971.

"New Metastable Autoionizing States of Highly Stripped Ions," Physics Department Colloquium, University of Tennessee, December, 1971.

"Spectra of Electrons Emitted by Fast, Metastable Ion Beams," Experimental Physics Seminar, Harvard University, December, 1971.

"Spectra of Electrons Emitted by Fast, Metastable Ion Beams," Physics Seminar, University of Virginia, January, 1972.

"Heavy Ion Atomic Physics," Colloquium Presented at Dr. Jose Balseiro Institute of Physics, Centro Atomico Bariloche, Bariloche, Argentina, May, 1972.

"Autoionization of Atoms Produced in Heavy Ion Collision," Invited Paper, in Proceedings of the ORNL Heavy-Ion Summer Study, Oak Ridge, Tennessee, AEC CONF-720669, 551 (1972).

"Metastable Autoionizing States," Invited Paper, presented at the Third International Conference on Beam-Foil Spectroscopy, Tucson, Arizona, October, 1972.

"Metastable States of Heavy-Ions," Physics Department Colloquium, University of Georgia, Athens, Georgia, December, 1972.

"Metastable Atomic States of Heavy Ions I: X-Ray Emitting States; II: X-Ray and Auger Emitting States; III: Auger Emitting States and Astrophysical Topics," lecture series presented at the Kansas State University in January, 1973. Other lecturers were D. Allan Bromley, Eugen Merzbacher, Donald Robson, H. Terry Fortune, J. D. Garcia, and Walter Greiner.

"Heavy Ion Atomic Physics Experiments at 1-4 MeV/nucleon Energies," Invited talk, presented at the University of California, Berkeley, September, 1973.

"Heavy Ion Atomic Physics Experiments at 1-4 MeV/nucleon Energies," Invited talk, presented at the Joint Institute for Laboratory Astrophysics, Boulder, Colorado, September, 1973.

"Recent Heavy Ion Atomic Physics Experiments at Oak Ridge," Colloquium, Virginia Polytechnic Institute, October, 1973.

"Recent Heavy Ion Atomic Collisions Experiments at Oak Ridge," Colloquium, University of North Carolina, April, 1974.

"Recent Coherent Excitation and XUV X-Ray Spectroscopy Experiments of Some Interest to Nuclear and Optical Physicist," Invited Paper, Bull. Am. Phys. Soc. 19, 586 (1974).

"Recent Heavy Ion XUV X-Ray and Coherent Excitation Experiments at Oak Ridge," Invited talk, Bell Telephone Laboratories, Murray Hill, May, 1974.

"Accelerator Based Atomic Physics," Physics Department Colloquium, University of Georgia, January, 1975.

"Heavy Ion Atomic Physics Experiments with Accelerators," Invited seminar, University of Washington, February, 1975.

"Report on the Fourth International Conference on Beam-Foil Spectroscopy," Invited seminar, Hahn-Meitner Institute, Berlin, W. Germany, September, 1975.

"Novel Aspects of Recent Heavy Ion Atomic Physics Experiments," Invited seminar, the University of Freiburg, W. Germany, September, 1975.

"Applications of Beam-Foil Spectroscopy to Atomic Collisions in Solids," Invited Paper, presented at the Fifth International Conference on Atomic Collisions in Solids, Amsterdam, the Netherlands, September, 1975.

Invited Paper, "Highly Ionized Ions." Bull. Am. Phys. Soc. 21, 186 (1976).

"Highly Ionized Ions," Physics Department Colloquium, Vanderbilt University, March, 1976.

"Puzzles in the Atomic Physics of Heavy Ions," Invited Seminar, Physics Division, Oak Ridge National Laboratory, May, 1976.

"Violent Collisions of Highly Ionized Ions," Physics Department Colloquium, Georgia State University, June, 1976.

Invited Paper, "Overcoming the Doppler Limitation in Beam-Foil Experiments by Target Ion Spectroscopy," presented at the Fourth Conference on Application of Small Accelerators, Denton, Texas, October, 1976, Bull. Am. Phys. Soc. 21, 1333 (1976).

Invited Paper, "High Ionization-Excitation States of Ne^{q+} Ions and their Mass-Dependent Symmetric Collision Interactions," presented at the Annual Meeting of the American Pnyscial Society, Division of Electron and Atomic Physics, Lincoln, Nebraska, December, 1976, Bull. Am. Phys. Soc. 21, 1250 (1976).

"Highly Ionized Ions and their Symmetric Collision Interactions," Physics Depart. Colloquium, University of Virginia, Charlottesville, January, 1977. Also presented at the Physics Depart. Colloquium, University of Arizona, Tucson, Arizona, in January, 1977, North Carolina State University, Raleigh, in January, 1977; and at the Physics Department Colloquium, University of Oklahoma, Norman, in February, 1977.

Invited paper, "Contributions of Beam-Foil Spectroscopy to Oscillator Strengths of Interest in High Temperature Plasmas," presented at the American Physical Society-Topical Conference on Atomic Processes in High Temperature Plasmas, Knoxville, February, 1977.

"The Beam Foil Spectroscopy Program of Oak Ridge", Invited Seminar, presented at the Nobel Institute-Research Institute for Atomic Physics, Stockholm, Sweden, March, 1977.

"Atomic Structure and Collisions of Highly Ionized Atoms", Invited Seminar, presented at the University of Aarhus, Aarhus, Denmark, March, 1977. Also presented at the University of Copenhagen, Copenhagen, Denmark, March, 1977.

"Charge State Dependence in Ion-Atom Collisions", Invited Seminar presented at the Swiss Federal Institute of Technology, Zürich, Switzerland, April, 1977.

"Physics of Collisions of Highly Charged Projectiles with Atoms and Molecules", Physics Department Colloquium,presented at Texas A & M University, College Station, Texas, May, 1977.

Invited paper, "Multiple Electron Rearrangement in Heavy Ion-Atom Collisions," presented at the Gordon Research Conference on Atomic Physics, Wolfsborough, New Hampshire, July, 1977.

"Multiple Electron Transitions in Collisions of Highly Charged Projectiles with Atomic and Molecular Targets", Invited Seminar, presented at the University of Frankfurt, Frankfurt/M Germany, September, 1977. Also presented at the Gesellschaft für Schwerionenforchung, Darmstadt, Germany, September, 1977.

"The Violent Many-Electron Chemistry of Highly Charged Ions", Physics Department Colloquium, University of Oregon, November, 1977. Also presented at the University of Washington, November, 1977.

OTHER SOURCES OF SUPPORT: SUBMISSIONS STATEMENT

A two year grant from the National Science Foundation at an annual support level of $59,750 commenced June 1, 1977. Further funding is contingent upon NSF renewal approval for any period beyond May 30, 1979. This NSF grant provides 52% of the direct support of our program and about 22% of the total support. Present ONR support provides 48% of our direct external support; this is the first year in which ONR has not been able to supply more than 50% of our direct external support. There is no other direct continuing funding of our program. Indirect support is discussed in the section Institutional Participation.

This proposal is not presently under consideration by any other agency.

INSTITUTIONAL PARTICIPATION AND BUDGET NOTES

In the past five contract years, the University of Tennessee purchased equipment in excess of $160,000 valuation in support of our ONR funded work. The University also provided in excess of 6,000 hours of machine shop time at no direct cost. It will be noted these amounts vastly exceed the University's corresponding legal cost sharing commitments. Because of static enrollment and other budget pressures, it is not assured that the University can continue to exceed its cost sharing commitments by so generous a margin. The Physics Department Head has, however, assured us of maximal help within his ability to provide it. With respect to the teaching release cost sharing provisions, the University has consistently released one-half of the time of the affected academic personnel as opposed to the one-third time commitment called for.

The very considerable indirect support afforded by this work through the use of the national facilities at ORNL and similar installations has already been discussed in the section on Facilities. For several additional reasons detailed below, it is anticipated that the direct contract costs of the proposed research amount to appreciably less than half of the total cost of the proposed research.

This proposal asks for sufficient funds to employ the personnel needed to carry out the proposed research and to continue development of our new instruments in future accelerator experiments, at the Oak Ridge National Laboratory, the Brookhaven National Laboratory, the German National Heavy Ion Accelerator (Unilac/GSI), and certain other sites. Salaries for two postdoctoral research associates and the equivalent for one graduate student are budgeted, together with summer salary for the principal investigator. Considering the several distinct kinds of experiments mentioned in the abstract, an operating staff of this size seems reasonable. Other significant budget requests include funds for experimental equipment specific to the proposed work, travel funds to permit visitors from other institutions to join us in collaborative experiments, travel funds to permit members of our users' group to travel to accelerators more remotely located than Oak Ridge, and some salary support for shop personnel and/or technical support help. The cost of transporting heavy equipment and personnel to remotely located accelerator sites accounts for the size of our travel budget request. It is felt that the ability to travel to suitable accelerator facilities as an experiment requires is an important aspect of our program. A compensating advantage is that the applicable overhead rate on salaries is that appropriate to off-campus sites, a rate about half that applying for on-campus projects.

The far above average institutional support of our work (as noted above) significantly reduces direct costs, as does the free use of accelerator and other facilities at the national laboratories mentioned.

Our principal need in carrying out the proposed experiments is thus for sufficient personnel to enable their pursuit and completion. As is evident from the various sections of this proposal dealing with facilities and equipment already available, we are with few exceptions well equipped to carry out the proposed work. We enjoy the use of first-rate national facilities. Qualified scientific research personnel are our greatest continuing programmatic need. There is no other means available to us other than through this proposal for us to support such personnel. While UTK has been exceptionally generous to our program in providing equipment, its budget legally permits retention of personnel for instructional purposes only. In an era of level enrollments and hence instructional personnel ceilings, support for university research personnel through the mechanism of this proposal is the only realistic hope we have for carrying on these projects. While the $5,000 increase in annual support level from ONR we received one year ago was especially welcome in view of the absence of any increase whatever in the two prior years, the average annual increase in support level has thus been $\sim$ 3%. The result has been contraction in the fraction of direct support provided by ONR to less than a 50% share. This proposal requests sufficient additional funds to reestablish a full 50% support level for our program.